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(71) Applicant: FONAR CORPORATION [US/US]; 110 Marcus Drive, Melville, NY 11747 (US).

(72) Inventors: SHENOY, Rajendra, K. ; 15 Eva Path, Commack, NY 11725 (US). WOLF, Robert, B. ; 157 Maple Street, Medford, NY 11763 (US).

(74) Agents: NELSON, John, R. et al.; Lerner, David, Littenberg, Krumholz & Mentlik, 600 South Avenue West, Westfield, NJ 07090-1497 (US).

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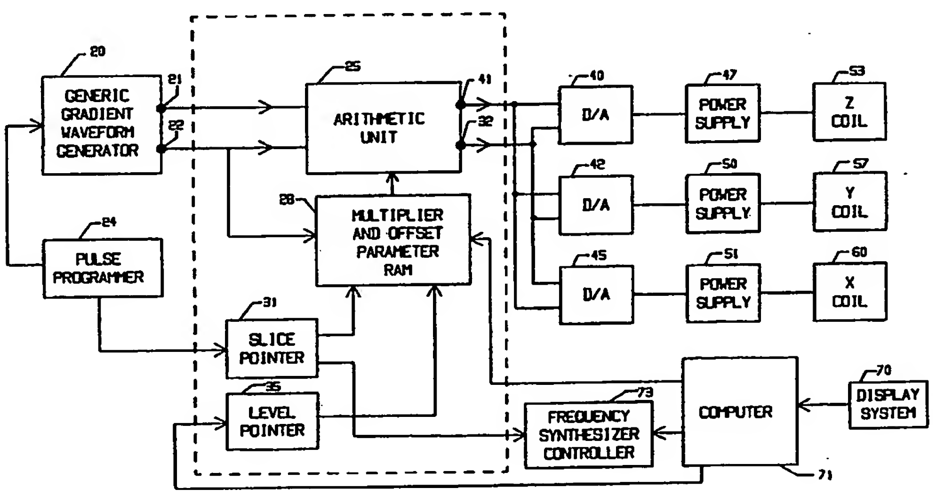

(57) Abstract

An apparatus for obtaining NMR image data from preselected planes having any desired orientations relative to three orthogonal reference axes, which pass through desired portions of an object utilizes a multiplier and offset parameter RAM (28) which provides multiplier and offset terms corresponding to two angles associated with each selected plane. A generator (20) provides generic gradient waveforms to an arithmetic unit (25) which combines these waveforms with the multiplier and offset parameters from the RAM to create waveforms, which when applied to the gradient coils (53, 57 and 60) of an NMR apparatus, rotate the slice selector, the read out, and the phasing coding gradients to produce resulting slice selector gradients which are orthogonal to the preselected planes, thereby permitting image data to be obtained from planes or arbitrary orientation. A method in accordance with the apparatus of the present invention is also disclosed.

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DESCRIPTION

APPARATUS AND METHOD FOR GENERALIZED OBLIQUE MAGNETIC RESONANCE IMAGING

Technical Field

The present invention relates generally to magnetic resonance imaging and, more particularly, to a method and apparatus capable of obtaining NMR image data from selected planes, in an object, having any desired dispositions relative to three reference orthogonal axes.

Background Art

Conventional prior art magnetic resonance imaging apparatus and techniques entail oblique imaging which permits image data to be taken from a plane through an object which is at an angle to one of the three orthogonal axes. Also, the prior art in that domain entails multi-slice imaging which permits image data, in one scan, to be taken in a plurality of parallel planes, through the object, which are orthogonal to one of the three orthogonal axes, which are uniformly spaced one from the other, and whose image centers are all aligned.

Further, present magnetic resonance imaging apparatus entail a combination of the above methods in an oblique multi-slice technique which was disclosed by FONAR Corporation in a technical exhibit at a conference of the Radiological Society of North America in November, 1984. Referring to Figure 1, the oblique multi-slice technique permits images of an object 11, in one scan, to be obtained in planes, such as 1-7 extending into the paper, which are disposed at an angle P relative to one of the three primary orthogonal axes, arbitrarily designated Y. However, the planes 1-7 within a given scan are parallel, and have a constant distance D therebetween. Further, the positioning of the center of the image corresponding to the plane 1 determines the center of the image corresponding to each of the planes 2-7. That is, when the center of the image corresponding to the plane 1 is selected to be at a point 12 on the object 11, the centers of the images of the planes 2-7

are necessarily therefore at, respectively, points 13-18. The selection of the center of the image corresponding to the plane 1 at the point 12 determines the centers of the images corresponding to the other planes 2-7.

Accordingly, in the prior art, to generate an image from a first plane disposed at a first angle relative to one of the orthogonal axis, and to generate an image from a second plane disposed at a second angle, two scans are required. A full scan including the first plane disposed at the first angle must be taken, and then a second full scan including the second plane disposed at the second angle must be taken. Similarly, if the distance between planes is desired to be varied, then once again several scans are required, each having one of the desired distances between planes. Further, if the centers of the images corresponding to two or more planes are not desired to be aligned as in the prior art, then a separate scan is required to center the image of a particular plane. For example, to center the image corresponding to the plane 6 at the point 19 on the object 11, a second scan would be required; since, in the first scan the center of the image corresponding to the plane 6 coincides with the point 17.

Accordingly, to obtain images from planes which are not parallel to each other, or which possess varying distances between one another, or which have misaligned image centers, requires additional scans and time that is wasted in capturing nonessential information.

Further in accordance with a copending application of the present assignee entitled "Apparatus And Method For Multiple Angle Oblique Magnetic Resonance Imaging," Serial No. 931,333 filed November 14, 1986, images may be obtained, in a single scan, from selected planes disposed at different angles, having varying distances therebetween, and having shifted image centers. In accordance with this invention, the selected planes are disposed orthogonal to, respectively, slice selector magnetic field gradients having directions which result

from rotating the direction of a reference slice selector gradient about the direction of a reference phase encoding gradient. The dispositions of the selected planes are limited by the corresponding single rotations of the slice selector gradient; the dispositions of the planes do not embrace all possible orientations.

Thus, there is a need for an apparatus and method which permit images to be obtained from planes having any preselected, arbitrary orientations relative to three reference orthogonal axes.

Disclosure of Invention

The present invention entails a method and apparatus for obtaining NMR image data from a plane having a preselected but arbitrary orientation relative to first, second and third orthogonal axes using nuclear magnetic resonance techniques.

A method in accordance with the present invention includes positioning an object in a static homogeneous magnetic field; and selecting a plane through a portion of the object. The object is subjected to a plurality of repetitions of a repetition sequence composed of NMR excitation and magnetic gradient field pulses. Each of the repetitions of the repetition sequence includes the steps of applying an excitation pulse and reading out of an NMR signal produced by the excitation pulse. The excitation pulse for the repetition sequence is applied at a predetermined frequency in the presence of a predetermined slice selector magnetic field gradient having a gradient direction extending perpendicular to the plane. The gradient direction of the predetermined slice selector magnetic field gradient corresponds to that of the first axis after a rotation of the first and the second axes by a first angle about the third axis, and thereafter a rotation of the first and the third axes by a second angle about the second axis. The predetermined frequency is chosen so that the application of the excitation pulse at the predetermined frequency only excites selected

nuclei in the selected plane. The plurality of repetitions of the repetition sequence are carried out in a manner to encode spatial information into a collection of NMR signals which are representative of NMR image data for the selected plane.

The present invention also entails a method for conducting an examination of an object along a selected plane using nuclear magnetic resonance techniques. The method comprises positioning an object in an NMR imaging apparatus. The apparatus includes means for generating a magnetic field; means for exciting selected nuclei to generate NMR signals and for reading of such NMR signals to provide a collection of NMR signals from selected regions of an object placed in the NMR imaging apparatus; and means for applying gradient magnetic fields. The apparatus further includes means for obtaining NMR imaging data from the collection of NMR signals, and means for producing an image from the NMR imaging data. The method further comprises operating the NMR imaging apparatus to obtain an NMR scout image for a portion of the object of the examination. While the object remains positioned in the NMR imaging apparatus, the scout image is used to select a first plane of the object for which NMR image data is to be obtained. The first plane is transverse to the scout plane. The NMR imaging apparatus is operated to obtain an NMR scout image corresponding to the first plane. While the object remains positioned in the NMR imaging apparatus, the scout image corresponding to the first plane is used to select a second plane of the object for which NMR image data is to be obtained. The second plane is transverse to the scout image corresponding to the first plane. A plurality of NMR sampling operations are conducted to obtain NMR imaging data from the second selected plane of the object. Each of the plurality of NMR sampling operations includes an NMR excitation operation and an NMR reading operation. The NMR excitation operations are carried out in a manner so as to excite selected nuclei in the second selected

plane, and the NMR reading operations are carried out in a manner to encode spatial information into the obtained NMR imaging data.

The present invention also entails a second method for conducting an examination of an object along a selected plane utilizing nuclear magnetic resonance techniques. The second method comprises positioning an object in an NMR imaging apparatus. The apparatus includes means for generating a magnetic field; means for exciting selected nuclei to generate NMR signals and for reading of such NMR signals to provide a collection of NMR signals from selected regions of an object placed in the NMR imaging apparatus; and means for applying gradient magnetic fields. The apparatus further includes means for obtaining NMR imaging data from the collection of NMR signals, and means for producing an image from the NMR imaging data. The second method further comprises operating the NMR imaging apparatus to obtain a first NMR scout image corresponding to a first plane through a portion of the object of the examination, and to obtain a second NMR scout image corresponding to a second plane.

While the object remains positioned in the NMR imaging apparatus, the first scout image is used to select a third plane transverse to the first plane, and the second scout image is used to select a fourth plane transverse to the second plane and displaced from the third plane. An intersection of the first plane and the third plane, and an intersection of the second plane and the fourth plane define a fifth plane. A plurality of NMR sampling operations are conducted to obtain NMR imaging data from the fifth plane. Each of the plurality of NMR sampling operations includes an NMR excitation operation and an NMR reading operation. The NMR excitation operations are carried out in a manner so as to excite selected nuclei in the fifth plane, and the NMR reading operations are carried out in a manner to encode spatial information into the obtained NMR imaging data.

A first apparatus in accordance with the present invention for obtaining NMR image data for planes through an object having selected, but arbitrary dispositions relative to first, second and third orthogonal axes includes a generic gradient waveform generator, and a slice pointer for outputting signals representing, respectively, the selected planes. A level pointer outputs signals representing, respectively, the repetitions of a repetition sequence. A RAM, coupled to the waveform generator and to the slice and level pointers, stores multiplier and offset parameters corresponding to each of the selected planes. The parameters for a selected plane are defined by a first and a second angle associated with that plane. An arithmetic unit, coupled to the waveform generator and the RAM, transforms generic gradient waveforms into waveforms that effect rotations of the directions of a slice selector magnetic field gradient, a readout magnetic field gradient, and a phase encoding magnetic field gradient by the first and second angles corresponding to a selected plane. In this fashion, a slice selector magnetic field gradient is generated having a direction orthogonal to that of the selected plane.

A second apparatus in accordance with the present invention permits NMR image data to be obtained for a plane, through an object, having a selected, but arbitrary, disposition relative to first, second and third orthogonal axes. The apparatus includes a computer for precalculating gradient waveforms corresponding to the selected plane. The gradient waveforms are defined by a first and a second angle associated with the orientation of the plane relative to the three axes. The computer outputs these waveforms to a generator where they are stored, and output to effect rotations of the directions of a slice selector magnetic field gradient, a read out magnetic field gradient, and a phase encoding magnetic field gradient by the first and second angles

associated with the selected plane. In this fashion, a slice selector magnetic field gradient is generated having a direction orthogonal to that of the selected plane.

The present invention permits NMR image data to be acquired from a selected plane through an object having any disposition relative to three orthogonal axes. That is, with the present invention, there are no limitations with respect to the orientation of a plane which may be taken through an object in order to acquire NMR image data therefrom. Image data may now be obtained from a plane passing through an object having any desired geometrical orientation relative to three reference orthogonal axes; such data may be elicited from a plane having any possible angular orientation.

Brief Description of the Drawings

Figure 1 is a schematic diagram utilized to explain the oblique multi-slice technique of the prior art.

Figure 2 is a schematic diagram of a repetition sequence entailing various waveforms applied in accordance with conventional NMR imaging techniques.

Figure 3 is a schematic diagram with a generic gradient waveform utilized in a preferred embodiment of the present invention.

Figure 4 is a diagram of orthogonal X and Z axes which are rotated by a angle "a" to produce orthogonal Z^1 and X^1 axes.

Figure 5 is a schematic diagram of the axes of Figure 4, considered as vectors, depicting the decomposition of the Z^1 and X^1 vectors into Z and X components.

Figure 6 is a schematic diagram of the X^1, Y^1 and Z^1 axes of Figure 4, depicting a rotation of the Y^1 and Z^1 axes about the X^1 axis by an angle "b" to produce X^{11}, Y^{11}, and Z^{11} axes.

Figure 7 is a schematic diagram of the Y^1, Z^1, Y^{11}, and Z^{11} axes of Figure 6, considered as vectors,

depicting the decomposition of Y^{11} and Z^{11} into Y^{1} and Z^{1} components.

Figure 8 is a schematic diagram of a display system and a cursor thereon utilized with a preferred embodiment of the present invention.

Figure 9 is a schematic diagram of planes passing through selected portions of an object, for providing image data for a display system utilized with a preferred embodiment of the present invention.

Figure 10 is a schematic diagram of a display system of Figure 8 depicting an operation utilized in conjunction with a preferred embodiment of the present invention.

Figure 11 is a block diagram of an apparatus of a first preferred embodiment of the present invention.

Figure 12 is a schematic diagram of a display system utilized in a second mode, in accordance with a preferred embodiment of the present invention.

Figure 13 is a schematic diagram depicting the timing of operations for fifteen slices during one repetition time interval of a multi-slice NMR imaging technique.

Figure 14 is a block diagram of an apparatus of a second preferred embodiment of the present invention.

Identical numerals in different figures refer to identical elements.

Best Modes of Carrying Out Invention

The present invention entails a method and apparatus for obtaining NMR image data from a selected plane in an object having an arbitrary orientation relative to three reference orthogonal axes.

Referring to Figure 2, in order to construct images of an object, present day NMR imaging apparatus generally utilize magnetic field gradients for selecting a particular slice or plane of the object to be imaged and for encoding spatial information in signals provided by the object. For instance, one conventional technique involves subjecting an object to a continuous static

homogeneous field extending along a first direction and to sets of sequences of orthogonal magnetic field gradients which each generate a magnetic field component in the same direction as the static field but whose strengths vary along the direction of the gradients. In accordance with this known technique, nuclear spins in a selected plane are excited by a selective RF pulse in the presence of one of the magnetic field gradients, the frequency of the selective RF pulse corresponding to the Larmour frequency for only the selected plane of the object as determined by the magnetic field gradient imposed on the static magnetic field. Conveniently, the applied magnetic field gradient is designated the slice selector gradient. The selected plane will thus extend in a direction perpendicular to the gradient direction of the slice selector magnetic field gradient. This gradient is generated by applying a waveform designated SS(t) to a coil disposed along one of the three orthogonal axes. The excited selected spins are then subjected to the other magnetic field gradients, which can be designated the readout and phase-encoding magnetic field gradients, utilizing a plurality of repetitions in which the amplitude of the phase-encoding gradient is varied for each repetition and in which the readout gradient is applied during the reading out of the generated NMR signals. The readout magnetic field gradient is generated by a waveform designated RO(t) applied to a coil disposed along a second of the three orthogonal axes. The phase-encoding magnetic field gradient is generated by applying a waveform designated PE(t) to a coil disposed along the third of the three orthogonal axes. The received NMR signals are then transformed utilizing conventional two-dimensional Fourier transform techniques. The readout magnetic field and phase-encoding magnetic field gradients serve to encode spatial information into the collection of NMR signals so that two-dimensional images of the NMR signals in the selected plane can be constructed. As will be

appreciated, during the scanning sequence, the various magnetic field gradients are repeatedly switched on and off at the desired intervals. Such a two-dimensional Fourier transform imaging technique and the pulse sequence for such a technique is described in the book entitled Nuclear Magnetic Resonance Imaging in Medicine, published in 1981 by Igaku-Shoin, Ltd., Tokyo, and is sometimes known as spin-warp imaging.

Furthermore, many NMR imaging schemes today rely on the collection of spin-echo NMR signals rather than free induction decay (FID) signals. FID NMR signals are achieved by application of an RF excitation pulse and then reading out of the produced signal. The present invention may be utilized with NMR imaging techniques which employ either spin-echo NMR signals, or free induction decay NMR signals.

Referring to Figure 2, in utilizing the spin-echo signals, a 90 degree RF excitation pulse is followed by the application of a 180 degree rephasing RF pulse at a predetermined time interval after the 90 degree pulse. This produces a spin-echo signal at a corresponding time interval after the application of the 180 degree RF pulse. In NMR parlance, the time of the produced spin-echo NMR signal after the 90 degree RF excitation pulse is designated as TE (for time of echo). Thus the 180 degree RF pulse is applied at a time interval of TE divided by 2 after the 90 degree RF pulse.

The technique of multi-slice imaging has been developed for obtaining NMR images from a multiple number of parallel planes of the object by exciting the nuclei in the planes and reading out NMR signals therefrom during a single scan. More particularly, in multi-slice imaging, the slices or planes in the imaging volume are excited one after another during different portions of the interval between repetitions by packing an integral number of slice excitations between successive excitations in one particular plane or slice. For example, when selective RF pulses are applied in the

presence of a magnetic field gradient, only a limited region of the object is excited due to satisfaction of the resonance conditions. Accordingly, different frequencies will excite different parts of the object. As the repetition sequence for any particular slice involves an excitation followed by reading of the new signal and then followed by a recovery interval before applying the excitation pulse in a subsequent repetition, the nuclei in differing regions or planes can be excited during the recovery interval for one particular plane, thus efficiently utilizing the recovery time interval to selectively excite nuclei and read out NMR signals in other planes. Generally, the number of planes for which NMR images can be obtained is dependent on the recovery time interval between successive excitation pulses in a single plane and the sequence interval required for exciting and reading out of a NMR signal in one plane plus the time for switching of the gradients. For example, in connection with a spin-echo imaging sequence, the slice interval will correspond to the time necessary to apply a 90 degree excitation RF pulse, to apply a 180 degree rephasing RF pulse, to observe the echo produced thereby, and to raise and lower the appropriate gradients. During the portion of a repetition sequence following the sequence time interval, additional selected planes can be sequenced utilizing different frequencies in a consecutive manner.

Since the recovery time before reapplying an excitation pulse in connection with NMR images is generally long in comparison to the time needed to apply the excitation pulse, the rephasing RF pulse and the reading of the signals (together with the time needed to switch the appropriate gradients on and off), it is apparent that NMR signals can be generated and read out for a number of planes within the overall repetition time interval. For example, it is convenient to let TS represent a sequence time interval needed for a single slice to apply a 90° RF pulse, a 180° rephasing RF pulse,

to read out the spin-echo signal and the time needed to raise and lower the appropriate gradients. A number of slices or planes for which imaging data can be obtained is thus equal to the largest integral number obtained from dividing the repetition time T_{rep} by the sequence time interval TS.

Referring to Figure 13, there is shown a schematic diagram of the scheme for exciting selected nuclei in each of 15 planes, and for collecting the NMR imaging data from the corresponding plane in a multi-slice technique for one repetition interval, utilizing the repetition sequence discussed hereinabove with reference to Figure 2. In Figure 13, the overall repetition interval T_{rep} (along the horizontal axis) has been divided into 15 equal time slice intervals, TS. The vertical axis represents a number of slices of planes for which imaging data is to be collected, and has been labeled 1-15 to represent 15 different planes. Thus, imaging data for the 15 different planes or slices of an object are obtained during each repetition. Also, since the number of planes correspond to the number of different frequencies for the RF pulses, the vertical axis in Figure 13 has also been labeled with frequencies f_1-f_{15}. The term "P" is utilized to represent the operations for exciting selected nuclei and reading out of the generated NMR signal (together with the operations for switching on and off the appropriate gradient coils), corresponding to the intervals 1-4 depicted in Figure 2.

In connection with the multi-slice imaging sequence, the P operation for each slice or plane within the overall repetition interval T_{rep} occurs during a corresponding one of the 15 sequence time intervals, TS, with no two P operations occurring during the same interval TS.

Thus, in conventional multi-slice imaging, during a first sequence interval TS of the repetition sequence, a 90° RF excitation pulse, and a 180° rephasing pulse are applied at a first frequency f_1 and the

produced spin-echo signal then read out. This NMR signal will be representative of an NMR signal for nuclei in the first plane. Thereafter, during the recovery interval for the excited nuclei in the first plane, another sequence of a 90° RF excitation pulse, a 180° rephasing pulse and the reading out of the spin-echo NMR signal, with appropriate switching of the gradients, is carried out during the second sequence interval TS. This latter signal is representative of NMR signals from nuclei in the second plane. Thereafter, subsequent sequences of excitation, rephasing and reading out of NMR signals are carried out for the other planes in subsequent sequence intervals TS, when the excited nuclei in the first two planes are relaxing during their respective recovery intervals.

Accordingly, in a multi-slice NMR imaging method, consecutive sets of pulses and reading out of signals, at different frequencies, can be accomplished in one repetition time interval T_{rep}. In particular, the various slices or planes in the object being imaged are excited one after another, and the appropriate sequence interval, with the overall repetition rate for one slice being utilized to pack an integral number of slice intervals between successive excitations of the same slice. Each of the RF excitation and rephasing pulses is applied at a different frequency so as to excite a different slice or plane of the object. A single frequency only repeats itself once for each plane during the repetition time interval T_{rep}.

The slice selector magnetic field gradient is disposed along one of the three orthogonal axes, which may arbitrarily be designated as the Z axis. Similarly, the readout and the phase-encoding magnetic field gradients may arbitrarily be designated as disposed along the X and Y axes. Referring to Figure 3, a generic waveform 10 is depicted from which the slice selector gradient waveform and the readout gradient waveform may be generated. The waveform 10 rises from an initial

value of -.5 to a maximum value of .5, after which it descends to its minimum of value of -1.5, thereafter rises once again to its maximum of .5, and then dips, finally, to once again -.5. The ideal slice selector gradient waveform depicted in Figure 2 is simply the waveform 10 shifted upwardly by .5. That is, the amplitude of the slice selector gradient waveform at any time is merely that of the waveform 10 plus .5. Accordingly, the ideal slice selector gradient waveform possesses two flat peaks of amplitude 1 with a valley therebetween dipping to -1 and for the remainder of the time is 0. Similarly, the readout gradient waveform is generated from the waveform 10 by taking the negative of the waveform 10 and adding .5 to it. That is, the amplitude of the ideal readout gradient waveform at any particular time is simply the negative of the value of the waveform 10 at that time to which .5 has been added. This produces an ideal readout gradient waveform which has an initial value of 1, dips to 0, rises to 2, dips again to 0, and rises again to 1. The phase-encoding magnetic field gradient waveform is distinct and not derivable from the generic waveform 10. Letting SS(t) represent the ideal slice selector gradient waveform, RO(t) represent the ideal readout gradient waveform, and G(t) represent the generic waveform 10, we have: $SS(t) = G(t) + .5$, and $RO(t) = -G(t) + .5$. However, in practice, owing to the characteristics of the particular NMR machine which is being utilized, an offset of other than exactly .5 may be required to generate, from the generic waveform 10, slice selector and readout waveforms which are nearly 0 in the required intervals. Thus, more generally $SS(t) = G(t) + A$, and $RO(t) = -G(t) + A$, where A is an offset term determined for the particular machine to which the waveforms will be applied.

Referring to Figure 4, three orthogonal axes X, Y and Z are depicted, with a rotation of the X and Z axes about the Y axis by an angle "a", to create orthogonal X^1 and Z^1 axes. The rotated Z axis is designated Z^1, the

rotated X axis is designated X^1, and the stationary Y axis is designated Y^1. Referring to Figure 5, which depicts the X, X^1, Z and Z^1 axes of Figure 4, considering the various axes to be vectors, one has the following:

$$Z^1 = \cos(a)Z - \sin(a)X,$$
$$X^1 = \sin(a)Z + \cos(a)X, \text{ and}$$
$$Y^1 = Y.$$

Thus, each of the rotated axes, considered as vectors, may be described as a linear combination of the X and Z axes, considered as vectors. Referring to Figure 6, the Z^1 and Y^1 axes of Figure 4 are now each rotated by an angle "b" about the X^1 axis, to create orthogonal axes Y^{11} and Z^{11}. Referring to Figure 7, which depicts the Y^1, Z^1, Y^{11} and Z^{11} axes of Figure 6, considering the various axes to be vectors, one has the following:

$$Z^{11} = \cos(b)Z^1 + \sin(b)Y^1,$$
$$Y^{11} = -\sin(b)Z^1 + \cos(b)Y^1, \text{ and}$$
$$X^{11} = X^1.$$

Substituting the expressions above for X^1, Y^1 and Z^1 into the equations for X^{11}, Y^{11} and Z^{11} gives:

$$Z^{11} = \cos(b)\ \cos(a)Z - \cos(b)\sin(a)X + \sin(b)Y,$$
$$Y^{11} = -\sin(b)\cos(a)Z + \sin(b)\sin(a)X + \cos(b)Y, \text{ and}$$
$$X^{11} = \sin(a)Z + \cos(a)X.$$

Each of the magnetic field gradients may be considered a vector pointing in the direction of the gradient. If the slice selector gradient in the Z direction is designated Z_{ss}, if a slice selector gradient in the Y direction is designated Y_{ss}, and if a slice selector gradient in the X direction is designated X_{ss}, then in accordance with the above equations, a slice selector gradient in the Z^{11} direction, designated $Z^{11}{}_{ss}$, is equal to $\cos(b)\cos(a)Z_{ss} - \cos(b)\sin(a)X_{ss} + \sin(b)Y_{ss}$. Similarly, if a phase encoding gradient in the Z direction is designated Z_{pe}, if a phase encoding gradient in the Y direction is designated Y_{pe}, and if a phase encoding gradient in the X direction is designated X_{pe}, then, in accordance with the above equations, a phase encoding gradient in the Y^{11} direction, designated

Y^{11}_{pe}, is equal to $-SIN(b)COS(a)Z_{pe} + SIN(b)SIN(a)X_{pe} + COS(b)Y_{pe}$. Further, if a read out gradient in the Z direction is designated Z_{ro}, and if a read out gradient in the X direction is designated X_{ro}, then, in accordance with the above equations, a read out gradient in the X^{11} direction, designated X^{11}_{ro}, is equal to $SIN(a)Z_{ro} + COS(a)X_{ro}$.

Thus the slice selector gradient in the Z^{11} direction may be generated from a linear combination of slice selector gradients in the X, Y and Z directions. The phase encoding gradient in the Y^{11} direction may be generated from a linear combination of phase encoding gradients in the X, Y and Z directions; and, the read out gradient in the X^{11} direction may be generated from a linear combination of read out gradients in the X and Z directions.

Conventional NMR imaging apparatus comprise X, Y and Z coils for generating magnetic field gradients in, respectively, the X, Y and Z directions. To generate a slice selector gradient in the Z direction, the slice selector waveform, SS(t), is applied to the Z coil. To generate a slice selector gradient in the Y direction, the slice selector waveform, SS(t), is applied to the Y coil. Similarly, to generate a slice selector gradient in the X direction, the slice selector waveform, SS(t), is applied to the X coil. A phase encoding gradient in the Z direction is created by applying the phase encoding waveform, PE(t), to the Z coil; a phase encoding gradient in the Y direction is created by applying the phase encoding waveform, PE(t), to the Y coil; and a phase encoding gradient in the X direction is created by applying the phase encoding waveform, PE(t), to the X coil. Similarly, a read out gradient in the Z direction is created by applying the read out waveform, RO(t), to the Z coil; and a read out gradient in the X direction is created by applying the read out waveform, RO(t), to the X coil. Thus, to generate a slice selector gradient in the Z^{11} direction, a phase encoding gradient in the Y^{11}

direction, and a read out gradient in the X^{11} direction, a waveform, COS(b)COS(a)SS(t) - SIN(b)COS(a)PE(t) + SIN(a)RO(t) is applied to the Z coil, a waveform -COS(b)SIN(a)SS(t) + SIN(b)SIN(a)PE(t) + COS(a)RO(t) is applied to the X coil, and a waveform SIN(b)SS(t) + COS(b)PE(t) is applied to the Y coil. This follows from grouping the waveforms associated with a particular axis required to generate gradients in the X^{11}, Y^{11} and Z^{11} directions.

Replacing each of the expressions SS(t) and RO(t) by their equivalents in terms of G(t) and A, one has:

the waveform applied to the Z coil is G(t)[COS(b)COS(a) - SIN(a)] + A[COS(b)COS(a) + SIN(a)] - SIN(b)COS(a)PE(t),

the waveform applied to the X coil is G(t)[-COS(b)SIN(a) - COS(a)] + A[-COS(b)SIN(a) + COS(a)] + SIN(b)SIN(a)PE(t), and

the waveform applied to the Y coil is G(t)SIN(b) + A SIN(b) + COS(b)PE(t).

In practice, a constant, denoted C_z, is calibrated for the Z coil, such that the waveform C_z SS(t) when applied to the Z coil provides a predetermined slice selector gradient, denoted G gauss per inch. Similarly, for the Y coil a constant, C_y is calibrated, such that a waveform C_y SS(t) when applied to the Y coil provides a predetermined magnetic field gradient of, preferably G gauss per inch. Further, a constant, C_x, is calibrated for the X coil, such that the waveform C_x SS(t) when applied to the X coil provides a predetermined magnetic field gradient, of preferably G gauss per inch.

The waveform C_xRO(t) when applied at maximum amplitude to the X coil generates the same magnetic field gradient as that resulting from applying the waveform C_xSS(t) at maximum amplitude to the X coil. The situation is analogous for C_yRO(t) and C_ySS(t) with respect to the Y coil, and C_zRO(t) and C_zSS(t) with respect to the Z coil. Thus, either SS(t) or RO(t) may

be utilized for a given coil to determine the corresponding constant which provides a predetermined magnetic field gradient, of preferably G gauss per inch. Once C_x, C_y and C_z are determined, they are fixed. Therefore, to calibrate the phase encoding waveforms used in conjunction with C_x, C_y and C_z for the corresponding coils, the amplitude of the phase encoding waveform PE(t) is adjusted to provide a predetermined magnetic field gradient, of preferably G gauss per inch. The corresponding adjusted phase encoding waveforms are denoted $PE_x(t)$, $PE_y(t)$ and $PE_z(t)$. Thus, the waveform $C_xPE_x(t)$ when applied to the X coil generates the same magnetic field gradient as that resulting from applying either $C_xSS(t)$ or $C_xRO(t)$ to the X coil. The situation is analogous, for $C_yPE_y(t)$ and $C_zPE_z(t)$.

Accordingly, to provide a slice selector gradient in the Z^{11} direction, a read out gradient in the X^{11} direction, and a phase encoding gradient in the Y^{11} direction having, respectively, predetermined values, the above waveform applied to the Z coil is multiplied by a constant, the above waveform applied to the X coil is multiplied by a constant, and the above waveform applied to the Y coil is multiplied by a constant. For gradients of G gauss per inch in the Z^{11}, Y^{11} and X^{11} directions, the above waveform applied to the Z coil is multiplied by C_z, the above waveform applied to the Y coil is multiplied by C_y, and the above waveform applied to the X coil is multiplied by C_x. Thus, in a preferred embodiment of the present invention, a waveform applied to the Z coil is $[G(t)[COS(b)COS(a) - SIN(a)] + A[COS(b)COS(a) + SIN(a)] - SIN(b)COS(a)PE_z(t)]\ C_z$, the waveform applied to the Y coil is $[G(t)SIN(b) + A\ SIN(b) + COS(b)PE_y(t)]\ C_y$, and the waveform applied to the X coil is $[G(t)[-COS(b)SIN(a) - COS(a)] + A[-COS(b)SIN(a) + COS(a)] + SIN(b)SIN(a)PE_x(t)]\ C_x$.

Referring to Figure 8, a display system 70 utilized in conjunction with a preferred embodiment of the present invention is depicted. Referring also to

Figure 9, image data from an object 81 in an NMR scanner taken in a plane 92 parallel to the Z-X plane and having a particular Y coordinate, Y_o, is displayed on the system 70. The image data in the plane 92 is obtained by initially applying a slice selector gradient along the Y axis, a read out gradient along one of the remaining two axes, and a phase encoding gradient along the remaining axis. A center 90 of the display system 70 corresponds to a center 91 of the NMR magnet. The object 81 appears in the plane 92 displayed on the system 70. A cursor 78, having a center 79 designated with a dot, is positionable on the system 70 via controls 76 and 72. To obtain image data for a selected, but arbitrary plane through a point 82 of the object 81, a two-step procedure is utilized. First, image data is taken for a plane orthogonal to the plane 92, through the point 82, at a desired angle "c" relative to the horizontal axis of the system 70. To accomplish this, the cursor 78 is positioned such that the center dot 79 of the cursor 78 coincides with the desired point 82 on the object 81, and the cursor 78 is rotated to the desired angle "c". To position the cursor 78 in this fashion requires moving the center dot 79 upwardly until it matches the vertical coordinate of the point 82, and then along the horizontal until the center dot 79 matches the horizontal coordinate of the point 82, and then rotating the cursor 78 about the center 79 to the angle "c". The center of the image corresponding to the plane defined by the cursor 78 will coincide with the point 82 of the object 81.

Referring to Figure 10, in the second step of the procedure, the plane defined by the cursor 78 in Figure 8 is displayed on the system 70. To obtain image data from a plane orthogonal to the plane displayed on the system 70, passing through the point 82, at a desired angle "d" relative to the horizontal axis of the system 70, the cursor 78 is positioned such that the center dot 79 of the cursor 78 coincides with the point 82 on the object 81 and the cursor 78 is rotated to the

desired angle "d". This plane is the selected plane from which image data is ultimately desired. Referring also to Figure 11, the display system 70 is coupled to a computer 71 to which is output the coordinate and angle information for the object point 82. That is, the computer 71 receives, from the system 70 the Y coordinate, Y_o, of the plane 92; the vertical and horizontal coordinate of the object point 82 relative to the center 90 system 70, for each of the two planes displayed thereon; and the angles "c" and "d" of the desired planes passing through the point 82. From these coordinates the location of the point 82 relative to the center 91 of the NMR magnet can be calculated. The slice selector, read out and phase encoding gradients have been calibrated such that the magnetic field strength changes in their respective directions in a predetermined amount per inch. Preferably, this change is uniform for each of the gradients and is G gauss per inch. Associated with a particular magnetic field strength is a particular RF frequency required to excite nuclei in a plane having that particular strength. Thus, a position of the point under consideration on the system 70 can be translated into corresponding frequencies associated with gradient planes passing through the point.

Referring to Figures 4 and 6, from the coordinate and angle information provided by the display system 70, the computer 71 can calculate the angles "a" and "b" necessary to rotate the gradient directions X, Y and Z to, respectively, X^{11}, Y^{11} and Z^{11} so that a slice selector gradient in the Z^{11} direction will be orthogonal to the selected plane defined by the cursor 78 in Figure 10. This is required to generate an NMR image corresponding to the selected plane.

A second technique can be utilized for obtaining image data from a selected, but arbitrary plane which passes through the point 82 of the object 81. Referring to Figure 9, image data is also taken in a plane 100 passing through a second portion of the object

81. This is accomplished, as before, by utilizing a slice selector gradient in the Y direction. The plane 100 has a Y coordinate Y_1. Referring also to Figure 12, the image corresponding to the plane 92 is displayed on the left side of the system 70; and the image corresponding to the plane 100 is displayed on the right side of the system 70. To obtain image data for a desired plane through the point 82 of the object 81, a cursor 105 is positioned such that its center coincides with the point 82, and the cursor is rotated to the desired angle "c". A cursor 107 appears on the right side of the system 70 in the same position as the cursor 105. That is, the cursor 107 replicates, on the right side of the system 70, the movement of the cursor 105 on the left side of the system 70. The cursor 107 is selectively positioned parallel to itself, displaced by the length of a line 108 which is orthogonal to the cursor 107. The cursor 105 and the displaced cursor 107 define the ultimately selected plane as follows. Referring also to Figure 9, the plane defined by the cursor 105, which is orthogonal to the image plane 92 displayed on the left side of the system 70, intersects the plane 92 along a line 150. Similarly, the plane defined by the displaced cursor 107, which is orthogonal to the image plane 100 displayed on the right side of the system 70, and parallel to the plane defined by the cursor 105, intersects the plane 100 along the line 160. The ultimately selected plane is that plane which passes through the lines 150 and 160. Thus, by defining a first plane with the cursor 105 that is orthogonal to the plane 92 at a desired angle, and then defining a second plane orthogonal to the plane 100, and displaced perpendicularly a desired distance from the first plane, an ultimately selected plane of any desired orientation can be defined by the intersection of the first plane with the plane 92, and the intersection of the second plane with the plane 100. Referring to Figures 9 and 12, images from additional planes parallel

to planes 92 and 100 may also be simultaneously displayed on the system 70. This provides further information for selecting an ultimate plane. The selection is made by positioning a first cursor on one image which is replicated on the other images, and displacing the relicated cursor parallel to itself, on a second selected image, to a desired position. As before, the original cursor and the displaced one define the ultimately selected plane.

As before, from the coordinate and angle information provided by the system 70, the computer 71 of Figure 11 can calculate the coordinates of the point 82 of the object 81 relative to the center 91 of the NMR magnet, and, referring to Figures 4 and 6, the angles "a" and "b" required to rotate the gradient directions X, Y and Z to, respectively, X^{11}, Y^{11} and Z^{11} so as to produce a slice selector gradient direction Z^{11} which is orthogonal to the selected plane. With a slice selector gradient in this direction, NMR image data may then be taken from the selected plane.

The computer 71 performs all the necessary calculations for transforming the data output by the system 70 into corresponding coordinates, and desired angles. Referring to Figure 11, a first embodiment of the present invention is depicted. The expression for the waveform applied to the Z coil above, when expanded, contains a constant coefficient of the generic waveform G(t), a constant term, and a constant coefficient of the phase encoding waveform $PE_Z(t)$. A coefficient of G(t) is designated a multiplier and equals [COS(b)COS(a) - SIN(a)] C_Z. The constant term is designated an offset and equals A[COS(b)COS(a) + SIN(a)] C_Z. The coefficient of $PE_Z(t)$ is also designated a multiplier and equals - SIN(b)COS(a)C_Z. Similarly, the waveform applied to the Y coil contains a multiplier term which is the coefficient of the generic waveform G(t), a multiplier term which is the coefficient of the waveform $PE_Y(t)$ and a constant term, designated an offset. The coefficient

of the waveform G(t) is $SIN(b)C_y$, the coefficient of the waveform $PE_y(t)$ is $COS(b)C_y$, and the constant term is A $SIN(b)C_y$. For the X coil, the multiplier of G(t) is $[-COS(b)SIN(a) - COS(a)]C_x$; the multiplier for the waveform $PE_x(t)$ is $SIN(b)SIN(a)C_x$; and the constant term is $A[-COS(b)SIN(a) + COS(a)]C_x$. These multiplier offset terms for the Z coil, Y coil and X coil waveforms are calculated by the computer 71 for each ultimately selected plane or slice from data corresponding to that slice output by the system 70. For example, for the ultimate slice corresponding to the cursor 78 of Figures 8 and 10, the system 70 outputs signals to the computer 71 indicating the relevant coordinate and angle information. In response, utilizing this data, the computer 71 determines the corresponding angles "a" and "b", and the multiplier and offset terms for the waveforms applied to the Z coil, the Y coil, and the X coil. These values, associated with the ultimate slice, are output by the computer 71 to a RAM 28 where they are stored. This is done, in sequence, for each of the ultimate slices taken through the object 81 via similar operations on the system 70. Further, in response to the data associated with each ultimate slice output by the system 70, the computer 71 calculates for each ultimate slice an RF excitation frequency and a frequency required to demodulate the corresponding NMR signal during the read out period. The two frequencies are output by the computer 71 to a frequency synthesizer control 73 where they are stored in sequence. A generic gradient waveform generator 20 contains the generic waveform G(t) stored in digital form. The generator 20 also stores the phase encoding waveforms $PE_x(t)$, $PE_y(t)$ and $PE_z(t)$ in digital form. Preferably, the generator 20 stores these particular waveforms; but, may store others that suffice for purposes of the present invention. A pulse programmer 24 controls the waveform generator 20 and a slice pointer 31. The computer 71 controls a level pointer 35. In response to the programmer 24, the

generator 20 outputs, from a terminal 21, words of stored waveform data corresponding to a particular axis. Simultaneously, a signal is output from a terminal 22 representing the axis corresponding to the output waveform data. For the X axis, a word of the digitally stored phase encoding waveform, $PE_x(t)$, and a word of the digitally stored generic waveform G(t) are output. For the Y axis, a word of the phase encoding waveform, $PE_y(t)$, and a word of the generic waveform G(t) are output. For the Z axis, a word of the phase encoding waveform $PE_z(t)$, and a word of the generic waveform G(t) are output. In the sequence of outputs from the terminal 22, the order of the axis is predetermined but not necessarily cyclical. That is, the outputs of the terminal 22 are not necessarily X, Y, Z, X, Y, Z, etc. or some fixed permutation thereof; each axis need not appear every three outputs. The exact order of the axis is predetermined; but, may be adapted to the needs of a particular situation. The outputs of the generator 20 are fed to an arithmetic unit 25. The output of the terminal 22 of the generator 20 is conveyed to the multiplier and offset parameter RAM 28. The slice pointer, in response to a pulse from the pulse programmer 24, outputs a signal to the RAM 28 and to the frequency synthesizer controller 73 indicating which of the ultimate slices, in the sequence of ultimate slices of the object 81, is to be taken. The level pointer 35 indicates which of the repetitions of the repetition sequence is to transpire, and conveys this information to the RAM 28 which also stores amplitude values for each of the repetitions. An output terminal 41 of the arithmetic unit 25 is coupled to digital-to-analog converters 40, 42, and 45. An output terminal 32 of the arithmetic unit 25 is also coupled to each of the digital-to-analog converters 40, 42 and 45. The terminal 41 provides waveform data for a particular axis, and the terminal 32 indicates the axis corresponding to that data. The digital-to-analog converters 40, 42 and 45 are coupled

to, respectively, power supplies 47, 50 and 51, which are coupled, respectively, to a Z coil 53, a Y coil 57, and an X coil 60, in the NMR apparatus.

In operation, the generic gradient waveform generator 20, in response to the pulse programmer 24, outputs from the terminal 21, words of waveform data corresponding to a particular axis. A signal indicating this particular axis, say the Z axis, is provided from the terminal 22. The waveform data and the axis signal are conveyed to the arithmetic unit 25 and the axis signal is conveyed to the multiplier and offset parameter RAM 28. The slice pointer 31 provides a signal to the RAM 28 indicating the particular ultimate slice from the sequence of ultimate slices on the system 70 from which images are to be generated. In response to the axis indicating signal from the generator 20, and the slice indicating signal from the slice pointer 31, the RAM 28 outputs the above-described multiplier and offset terms for the corresponding axis and ultimate slice. Specifically, for an input from the slice pointer 31 indicating the first ultimate slice corresponding to cursor 78 Figure 10, and an input from the generator 20 indicating the Z axis, the RAM 28 outputs the multiplier $[\mathrm{COS}(b)\mathrm{COS}(a) - \mathrm{SIN}(a)]\ C_z$, and outputs the multiplier $-\mathrm{SIN}(b)\mathrm{COS}(a)\ C_z$, and outputs the offset term $A[\mathrm{COS}(b)\mathrm{COS}(a) + \mathrm{SIN}(a)]\ C_z$. The arithmetic unit 25 multiplies the digital data output from the terminal 21 of the generator 20, representing the generic waveform $G(t)$ and the phase encoding waveform $PE_z(t)$, by the corresponding multiplier terms output by the RAM 28, and to this expression adds the offset term output by the RAM 28. A sum, which represents the waveform segment to be applied to the Z coil, is output in digital form from the terminal 41 of the arithmetic unit 25, and a signal indicating the corresponding Z axis is output from the terminal 32. The digital-to-analog converter 40 corresponding to the Z coil is accessed by the axis indicating signal output by the terminal 32, and the

digital data output by the terminal 41 is directed to the converter 40 where it is converted to analog. The output of the converter 40 is applied to the Z coil 53 after being increased in amplitude by the power supply 47. For the same output of the slice pointer 31, a similar operation is performed with respect to the Y axis to provide the corresponding waveform segment to the Y coil, and a similar operation is performed with respect to the X axis to provide the corresponding waveform segment to the X coil.

In this fashion, the Z coil, the Y coil, and the X coil, receive corresponding waveforms in a predetermined sequence. Referring to Figures 4 and 6, the waveforms applied to the X, Y and Z coils serve to rotate the slice selector gradient first by the angle "a" about the phase encoding axis Y, and then rotate the resulting slice selector gradient by the angle "b" about the resulting read out gradient direction X^1. With the slice selector, the read out, and the phase encoding gradient directions rotated in this fashion, the conventional NMR technique for eliciting signals representing image data is applied.

The process for generating an image from a plane selected according to the scheme corresponding to Figures 8 and 10, or Figure 12 is similar to the conventional NMR imaging technique, except that the waveforms are no longer necessarily the conventional ones indicated in Figure 2; but, the waveforms applied to the Z and X coils are each functions of the corresponding angles "a" and "b"; and the waveform applied to the Y coil is a function of the angle "b".

The above-described first apparatus of a preferred embodiment of the present invention calculates the slice selector, readout and phase encoding waveforms in real time, just before application to the corresponding magnet coils, and excitation of the corresponding slice. In this fashion, relatively little

memory is required for storage purposes; most quantities are merely calculated, as needed, then output.

Referring to Figures 8 and 10, with the first technique additional ultimate planes or slices for providing image data may be selected parallel to that defined by the cursor 78 by employing, in the first step of the selection procedure, additional cursors, such as a cursor 165 which is selectively positioned parallel to the cursor 78 via a control 73. A center 163 of the cursor 165 lies along a line which is orthogonal to the cursor 78 and passes through its center 79. Similarly, a third cursor 162 may be selectively positioned parallel to the cursors 78 and 165, with its center 163 aligned with the centers 79 and 164. The centers of the images corresponding to, respectively, the cursors 78, 165 and 162 will be at points on the object 81 corresponding to the centers 79, 164 and 163 of the corresponding cursors. In the second step of the procedure, images from the planes corresponding to the cursors 78, 165 and 162 are displayed on the system 70; and a second set of three cursors are positioned relative to, respectively, these planes, in parallel. In this fashion, the corresponding ultimately selected planes are parallel.

The additional cursors 165 and 162 may be utilized only in the second step of the procedure depicted in Figure 10 to obtain ultimate planes which are parallel to the first selected ultimate plane. In this case, the cursors 165 and 162 are selectively positioned parallel to the cursor 78. The ultimately selected planes corresponding to, respectively, the cursors 78, 165 and 162 are thus parallel. In all of these cases, the angle "c" and the angle "d" remain the same, only the coordinates of the centers of the additional cursors are altered.

Similarly, referring to Figure 12, with the second technique additional ultimate planes parallel to the first selected ultimate plane may be obtained by utilizing additional cursors such as a cursor 180 which

is displaced parallel to the cursor 105 on the left side of the system 70. On the right side of the system 70, as for the cursor 105, a replica of the cursor 180 appears as a cursor 185. The cursor 185 is displaced parallel to itself by a distance corresponding to the orthogonal line 109. This distance is equal to the distance of the line 108. In this fashion, a cursor 180, and a displaced cursor 185 define an ultimate plane which is parallel to the first selected ultimate plane defined by the cursor 105 and the displaced cursor 107. From the information provided by the second set of cursors, the computer 71 calculates corresponding coordinates and the corresponding angle of rotation of the gradients. Since the second selected plane is parallel to the first, the angles are the same.

Referring to Figure 14, a second apparatus of the present invention is utilized with the procedures described above, wherein only a first plane or a plurality of parallel planes are ultimately selected for imaging. The display system 70 provides the coordinate and angle information to the computer 71 which performs all the necessary calculations for transforming the data output by the system 70 into corresponding coordinates and desired angles. Specifically, the computer 71 calculates the "a" and "b" angles required to rotate the magnetic field gradients as depicted in Figures 4 and 6, to produce a slice selector magnetic field gradient having a direction orthogonal to that of the ultimately selected plane or planes. With these angles, the computer 71 precalculates for each of the above-described waveforms applied to the X, Y and Z coils the portion thereof not involving a phase encoding waveform. With each repetition of the repetition sequence, the computer 71 calculates the phase encoding waveform portion of each waveform, wherein the amplitude of the phase encoding waveform is adjusted in accordance with the two-dimensional Fourier transform technique, and adds this to the corresponding precalculated portion not

involving the phase encoding waveform. The resulting completely calculated waveforms for the X, Y and Z coils are output by the computer 71, for each repetition, to the generator 20 which stores the waveforms in digital form.

For example, for the waveform applied to the Z coil, the computer 71 precalculates the portion thereof not involving the phase encoding waveform, namely, $[G(t)[COS(b)COS(a)-SIN(a)] + A[COS(b)COS(a) + SIN(a)]]C_Z$. With each repetition of the repetition sequence, the computer 71 calculates the phase encoding waveform portion of the waveform. For the first repetition, this is $-SIN(b)COS(a)PE_Z(t)C_Z$, which is added to the above-precalculated portion to produce the complete waveform applied to the Z coil in the first repetition of the repetition sequence. In subsequent repetitions, the amplitude of the phase encoding waveform $PE_Z(t)$ is adjusted in the phase encoding waveform portion. This portion is added to the precalculated portion not involving the phase encoding waveform, to produce the complete waveform applied to the Z coil during the corresponding repetition in the repetition sequence.

The pulse programmer 24 controls the generator 20 in accordance with NMR multi-slice techniques. In response to the programmer 24, the generator 20 outputs, from the terminal 21, a word of stored waveform data corresponding to a particular axis. Simultaneously, a signal is output from the terminal 22 representing the axis corresponding to the output waveform data. In the sequence of outputs from the terminal 22, the order of the axes is predetermined but not necessarily cyclical. The outputs of the generator 20 are fed to the digital-to-analog converters 40, 42 and 45. The operation of the digital-to-analog converters 40, 42 and 45, the power supplies 47, 50 and 51, and the coils 53, 57 and 60 is as for the first apparatus of the present invention.

The operation of the second embodiment is similar to the above-described first embodiment except that the angles "a" and "b" do not change from ultimate slice to ultimate slice. In this regard, the operation of the second embodiment is similar to the conventional multi-slice technique, except that the waveforms applied to the Z and X coils are each functions of the angles "a" and "b", and the waveform applied to the Y coil is a function of the angle "b".

While the above-described embodiments of the present invention utilized image data on the system 70, this is not necessary. Referring to Figures 4 and 6, for purposes of the present invention, all that is required are the X, Y and Z coordinates of the point through which a plane is desired, and the angles "a" and "b" that produce a slice selector gradient in the direction that is perpendicular to the desired plane. The system 70 of Figure 8 provides this information; but, any source of this data, including direct input, suffices for the purposes of present invention.

Further, although the embodiments described above utilized slice selector, readout, and phase encoding gradients along specified axes, the various gradients may be permuted among the axes from slice to slice.

The present invention may be employed with the spin-echo NMR technique, the free induction decay (FID) technique, or with any NMR technique utilizing a slice-selected gradient.

The present invention also entails methods corresponding to the operations of the embodiments described above.

While the invention has been described in its preferred embodiments, it is to be understood that the words which have been used are words of description rather than limitation, and that changes within the purview of the appended claims may be made without

departing from the true scope and spirit of the invention in its broader aspects.

Industrial Applicability

The present invention pertains to a method and apparatus for obtaining NMR image data from a plane having a preselected but arbitrary orientation relative to first, second and third orthogonal axes. In a particular medical use of the method and apparatus of the present invention, a patient is disposed in an NMR imaging apparatus and a "scout" image of a portion of the patient's body is displayed on, for example, a screen. While the patient is lying in the NMR apparatus, an operator positions a cursor having a center, at an arbitrary position and orientation on the screen. Then, in accordance with the inventive method and apparatus, image data is provided from a second "scout" plane which is traverse to the portion of the patient's body that is displayed on the screen at the position and orientation indicated by the cursors. Then, while the patient remains positioned in the NMR apparatus, the operator positions another cursor at a second arbitrary orientation in the screen and in accordance with the inventive method and apparatus, image data is provided from the plane which is transverse to the second "scout" plane. Further, a plurality of such arbitrarily positioned and oriented planes may be obtained in the course of a single scan.

CLAIMS

1. A method for obtaining NMR image data from a plane using nuclear magnetic resonance techniques, comprising the steps of:

(a) positioning an object in a static homogeneous magnetic field;

(b) selecting a plane through a portion of said object; and

(c) subjecting said object to a plurality of repetitions of a repetition sequence composed of NMR excitation and magnetic gradient field pulses, each of said repetitions of said repetition sequence including the steps of applying an excitation pulse and reading out of an NMR signal produced by said excitation pulse, said excitation pulse for said repetition sequence being applied at a predetermined frequency in the presence of a predetermined slice selector magnetic field gradient having a gradient direction extending perpendicular to said plane, the method being characterized in that said gradient direction of said predetermined slice selector magnetic field gradient corresponds to that of said first axis after a rotation of said first and said second axes by a first angle about said third axis, and thereafter a rotation of said first and said third axes by a second angle about said second axis; said predetermined frequency is chosen so that said application of said excitation pulse at said predetermined frequency only excites selected nuclei in said selected plane, and said plurality of repetitions of said repetition sequence are carried out in a manner to encode spatial information into a collection of said NMR signals, said collection of said NMR signals being representative of NMR image data for said selected plane.

2. The method of Claim 1 further characterized in that Step (c) comprises generating said magnetic gradient field pulses of said repetition sequence via a first, a second, and a third waveform, which produce said predetermined slice selector magnetic field gradient.

3. The method of Claim 2 using an NMR imaging apparatus having first means for generating a first magnetic field gradient having a first direction along said first axis, and second means for generating a second magnetic field gradient having a second direction along said second axis, and third means for generating a third magnetic field gradient having a third direction along said third axis, the method being characterized in that the step of generating said magnetic field gradient pulses of said repetition sequence comprises applying said first waveform to said first means, said first waveform being of a form $[G(t)[COS(b)COS(a)-SIN(a)] + A[COS(b)COS(a) + SIN(a)] -SIN(b)COS(a)PE_z(t)]C_z$, where $G(t)$ is a predetermined gradient waveform, $PE_z(t)$ is a predetermined gradient waveform, and A and C_z are predetermined constants; applying said second waveform to said said second means, said second waveform being of a form $[G(t)[-COS(b)SIN(a)-COS(a)] + A[-COS(b)SIN(a) + COS(a)] + SIN(b)SIN(a)PE_x(t)]C_x$, where $PE_x(t)$ is a predetermined gradient waveform, and C_x is a predetermined constant; and applying said third waveform to said third means, said third waveform being of a form $[G(t)SIN(b) + A\ SIN(b) + COS(b)PE_y(t)]C_y$, where $PE_y(t)$ is a predetermined gradient waveform, and C_y is a predetermined constant and "a" is said first angle and "b" is said second angle.

4. A method for conducting an examination of an object along a selected plane using nuclear magnetic resonance techniques, comprising the steps of:

(a) positioning an object in an NMR imaging apparatus which includes means for generating a magnetic field, means for exciting selected nuclei to generate NMR signals and for reading of such NMR signals to provide a collection of NMR signals from selected regions of an object placed in said NMR imaging apparatus, means for applying gradient magnetic fields, means for obtaining NMR imaging data from said collection

of NMR signals and means for producing an image from said NMR imaging data;

(b) operating said NMR imaging apparatus to obtain a first NMR scout image corresponding to a scout plane of said object;

(c) while said object remains positioned in said NMR imaging apparatus, using said first scout image to select a first plane of said object for which NMR image data is to be obtained, said first plane being transverse to said scout plane, and said first plane having a first orientation relative to said scout plane;

characterized in that said method further comprises the steps of:

(d) operating said NMR imaging apparatus to obtain second NMR scout image corresponding to said first selected plane;

(e) while said object remains positioned in said NMR imaging apparatus, using said second scout image corresponding to said first selected plane to select a second plane of said object for which NMR image data is to be obtained, said second plane being transverse to said first selected plane; and

(f) conducting a plurality of NMR sampling operations to obtain NMR imaging data from said second selected plane of said object, each of said plurality of said NMR sampling operations including NMR excitation operation and NMR reading operation, said NMR excitation operations being carried out in a manner so as to excite selected nuclei in said second selected plane, and said NMR reading operations being carried out in a manner to encode spatial information into said obtained NMR imaging data.

5. The method of Claim 4 further characterized in that said step (f) comprises applying a first, a second, and a third waveform to said means for applying gradient magnetic fields, to produce a predetermined slice selector magnetic field gradient having a direction orthogonal to said second selected plane.

6. The method of Claim 5 wherein said means for applying gradient magnetic fields comprises first means for generating a first magnetic field gradient having a first direction, second means for generating a second magnetic field gradient having a second direction orthogonal to said first direction, and third means for generating a third magnetic field gradient having a third direction orthogonal to said first and second directions, said method being characterized in that said direction of said predetermined slice selector gradient is said first direction after a rotation of said first and second directions by a first angle about said third direction, and thereafter a rotation of said first and third directions by a second angle about said second direction; and further characterized in that said step of applying said first, second, and third waveforms comprises applying said first waveform to said first means, said first waveform being of a form $[G(t)[COS(b)COS(a) - SIN(a)] + A[COS(b)COS(a) + SIN(a)] - SIN(b)COS(a)PE_z(t)]C_z$, where $G(t)$ and $PE_z(t)$ are each predetermined gradient waveforms, A and C_z are each predetermined constants, and "a" is said first angle, and "b" is said second angle; applying said second waveform to said second means, said second waveform being of a form $[G(t)[-COS(b)SIN(a) - COS(a)] + A[-COS(b)SIN(a) + COS(a)] + SIN(b)SIN(a)PE_x(t)]C_x$, where $PE_x(t)$ is a predetermined gradient waveform, and C_x is a predetermined constant; and applying said third waveform to said third means, said third waveform being of a form $[G(t)SIN(b) + ASIN(b) + COS(b)PE_y(t)]C_y$, where $PE_y(t)$ is a predetermined gradient waveform, and C_y is a predetermined constant.

7. A method for conducting an examination of an object along a selected plane utilizing nuclear magnetic resonance techniques, said method comprising the steps of:

(a) positioning an object in an NMR imaging apparatus which includes means for generating a

magnetic field, means for exciting selected nuclei to generate NMR signals and for reading of such NMR signals to provide a collection of NMR signals from selected regions of an object placed in said NMR imaging apparatus, means for applying gradient magnetic fields, means for obtaining NMR imaging data from said collection of NMR signals and means for producing an image from said NMR imaging data; and

(b) operating said NMR imaging apparatus to obtain a first NMR scout image corresponding to a first plane through a portion of said object of said examination;

characterized in that said method further comprises the steps of:

(c) operating said NMR imaging apparatus to obtain a second NMR scout image corresponding to a second plane;

(d) while said object remains positioned in said NMR imaging apparatus, using said first scout image to select a third plane transverse to said first plane, and using said second scout image to select a fourth plane transverse to said second plane and displaced from said third plane, an intersection of said first plane and said third plane and an intersection of said second plane and said fourth plane defining a fifth plane; and

(e) conducting a plurality of NMR sampling operations to obtain NMR imaging data from said fifth plane, each of said plurality of NMR sampling operations including an NMR excitation operation and an NMR reading operation, said NMR excitation operations being carried out in a manner so as to excite selected nuclei in said fifth plane, and said NMR reading operations being carried out in a manner to encode spatial information into said obtained NMR imaging data.

8. The method of Claim 7 further characterized in that said step (e) comprises applying a first, a second, and a third waveform to said means for applying

gradient magnetic fields to produce a predetermined slice selector magnetic field gradient having a direction orthogonal to said fifth plane.

9. The method of Claim 8 wherein said means for applying gradient magnetic fields comprises first means for generating a first magnetic field gradient having a first direction, second means for generating a second magnetic field gradient having a second direction orthogonal to said first direction, and third means for generating a third magnetic field gradient having a third direction orthogonal to said first and second directions, said method being characterized in that said direction of said predetermined slice selector gradient is said first direction after a rotation of said first and second directions by a first angle about said third direction, and thereafter a rotation of said first and third directions by a second angle about said second direction; and further characterized in that said step of applying said first, second and third waveforms comprises applying said first waveform to said first means, said first waveform being of a form $[G(t)[COS(b)COS(a) - SIN(a)] + A[COS(b)COS(a) + SIN(a)] - SIN(b)COS(a)PE_z(t)]C_z$; applying said second waveform to said second means, said second waveform being of a form $[G(t)[-COS(b)SIN(a) - COS(a)] + A[-COS(b)SIN(a) + COS(a)] + SIN(b)SIN(a)PE_x(t)]C_x$; and applying said third waveform to said third means, said third waveform being of a form $[G(t)SIN(b) + ASIN(b) + COS(b)PE_y(t)]C_y$, where $G(t)$, $PE_x(t)$, $PE_y(t)$ and $PE_z(t)$ are each predetermined gradient waveforms, and A, C_x, C_y, and C_z, are each predetermined constants, and "a" is said first angle, and "b" is said second angle.

10. An apparatus for obtaining NMR image data for a plane through an object having a selected disposition relative to first, second and third orthogonal axes, comprising: means for providing generic gradient waveforms; and means, coupled to said providing means, for generating gradient waveforms that produce a

slice selector magnetic field gradient having a direction orthogonal to that of said plane, characterized in that said direction of said slice selector magnetic field gradient corresponds to that of said first axis after rotating said first and second axes by a first angle about said third axis and thereafter rotating said first and third axes by a second angle about said second axis.

11. The apparatus of claim 10, further characterized in that said generating means comprises means, coupled to said providing means, for providing multiplier and offset parameters corresponding to said first and second angles; and means, coupled to said generic gradient waveform providing means and to said multiplier and offset parameter providing means, for combining said generic gradient waveforms with said multiplier and offset parameters to produce said gradient waveforms.

12. The apparatus of claim 11 further characterized in that said multiplier and offset parameter providing means includes means for providing multiplier parameters $[COS(b)COS(a) - SIN(a)]C_z$, $-SIN(b)COS(a)C_z$, $SIN(b)C_y$, $COS(b)C_y$, $[-COS(b)SIN(a) - COS(a)]C_x$, and $SIN(b)SIN(a)C_x$, where "a" corresponds to said first angle, and "b" corresponds to said second angle, and for providing offset parameters $A[COS(b)COS(a) + SIN(a)]C_z$, $A\ SIN(b)C_y$, and $A[-COS(b)SIN(a) + COS(a)]C_x$, where A, C_x, C_y, and C_z are each predetermined constants; said generic gradient waveform providing means includes means for providing generic gradient waveforms G(t), $PE_x(t)$, $PE_y(t)$ and $PE_z(t)$; and said combining means includes means for generating waveforms having a form $[G(t)[COS(b)COS(a) - SIN(a)] + A[COS(b)COS(a) + SIN(a)] - SIN(b)COS(a)PE_z(t)]C_z$ and $[G(t)SIN(b) + ASIN(b) + COS(b)PE_y(t)]C_y$ and $[G(t)[-COS(b)SIN(a) - COS(a)] + A[-COS(b)SIN(a) + COS(a)] + SIN(b)SIN(a)PE_x(t)]C_x$.

13. An apparatus for obtaining NMR image data for a plane through an object having a selected

disposition relative to first, second and third orthogonal axes, comprising:

means for generating and outputting gradient waveforms that produce a slice selector magnetic field gradient having a direction orthogonal to that of said plane, characterized in that said direction of said slice selector magnetic field gradient corresponds to that of said first axis after rotating said first and second axes by a first angle "a" about said third axis, and thereafter rotating said first and third axes by a second angle "b" about said second axis; and means, coupled to said generating means, for controlling outputs of said generating means.

14. The apparatus of Claim 13 further characterized in that said generating means comprises means for generating gradient waveforms having a form $[G(t)[COS(b)COS(a) - SIN(a)] + A[COS(b)COS(a) + SIN(a)] - SIN(b)COS(a)PE_z(t)]C_z$, a form $[G(t)SIN(b) + ASIN(b) + COS(b)PE_y(t)]\ C_y$, and a form $[G(t)[-COS(b)SIN(a)-COS(a)] + A[-COS(b)SIN(a) + COS(a)] + SIN(b)SIN(a)PE_x(t)]C_x$, where $G(t)$, $PE_x(t)$, $PE_y(t)$ and $PE_z(t)$ are each predetermined waveforms, are A, C_x, C_y and C_z are each predetermined constants.

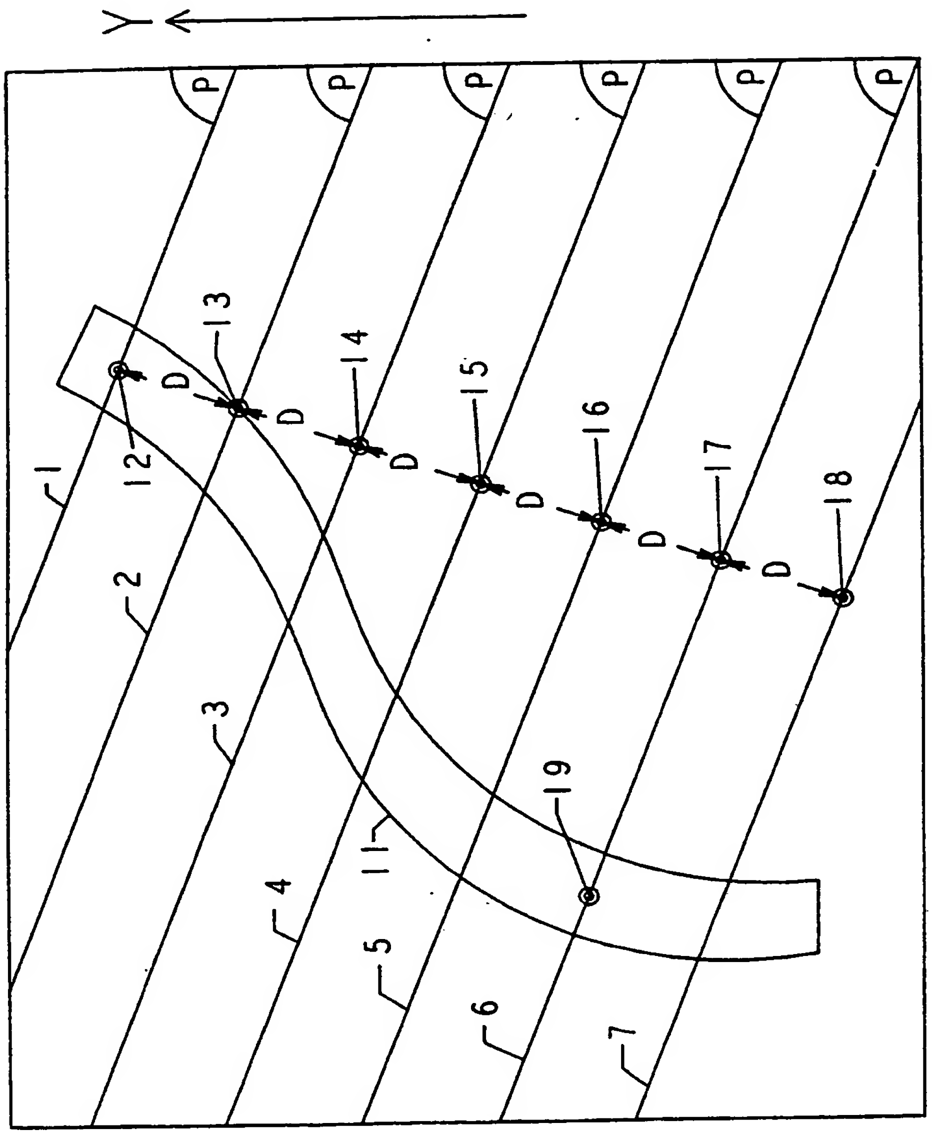
15. The method of claim 1 further characterized in that the method further comprises the following steps which are carried out during the same scan as the previous steps:

selecting a second plane through a portion of said object; and

subjecting said object to a plurality of repetitions of a repetition sequence composed of NMR excitation and magnetic gradient field pulses, each of said repetitions of said repetition sequence including the steps of applying an excitation pulse and reading out of an NMR signal produced by said excitation pulse, said excitation pulse for said repetition sequence being applied at a second predetermined frequency in the presence of a second predetermined slice selector

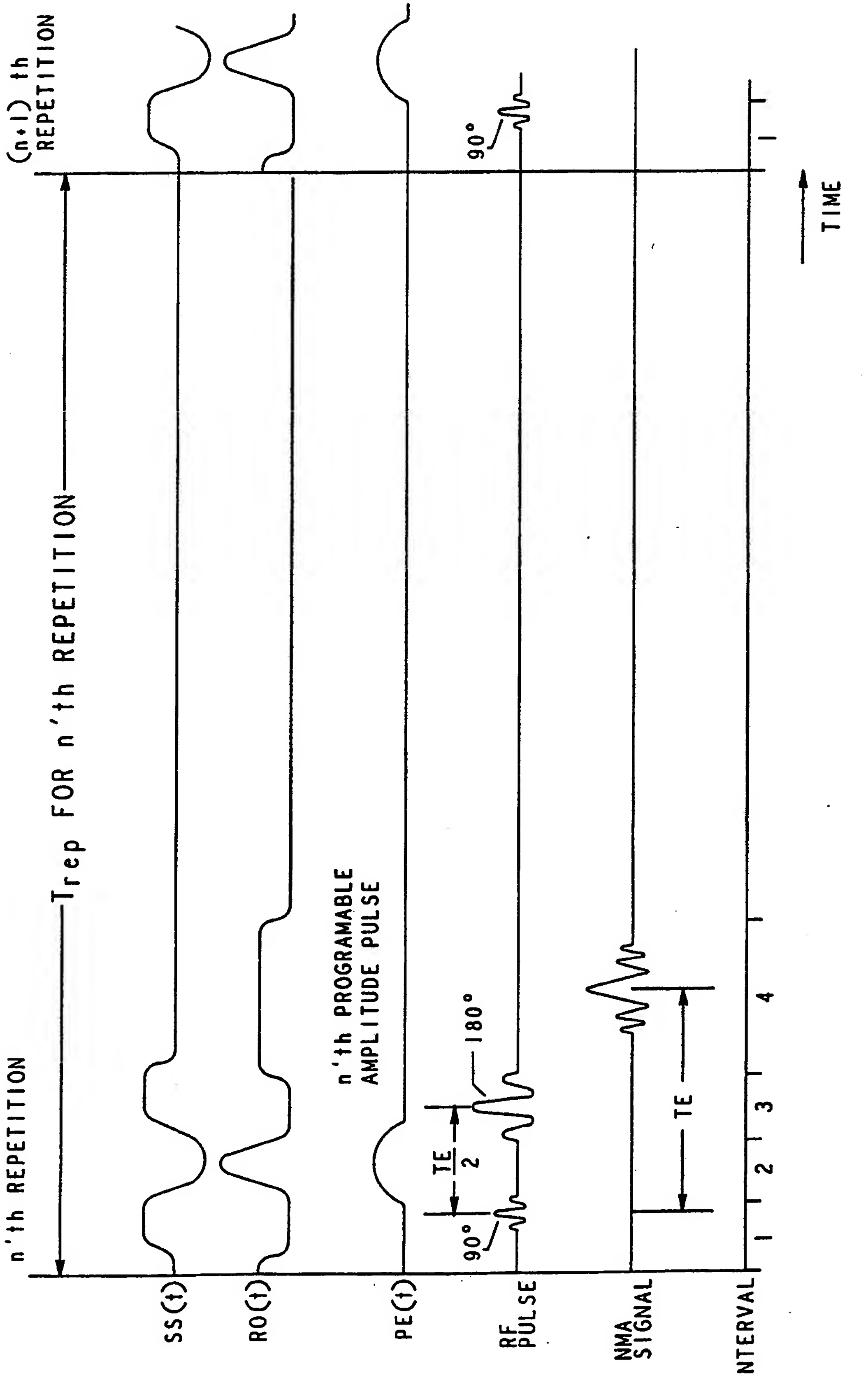
magnetic field gradient having a gradient direction extending perpendicular to said second plane, said gradient direction of said second predetermined slice selector magnetic field gradient corresponding to that of any one of said three axes after a rotation of said any one of said three axes and any second one of said three axes by another first angle about the remaining third one of said three axes, and thereafter a rotation of said any one of said three axes and said remaining third one of said three axes by another second angle about said any second one of said three axes, said second predetermined frequency being chosen so that said application of said excitation pulse at said second predetermined frequency only excites selected nuclei in said second selected plane, and said plurality of repetitions of said repetition sequence being carried out in a manner to encode spatial information into a collection of said NMR signals, said collection of said NMR signals being representative of NMR image data for said second selected plane;

wherein the location of the center of said first and second planes are arbitrary, said first angle and said another first angle are arbitrary, and said second angle and said another second angle are arbitrary.



PRIOR ART

FIG. 1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(n+1) th REPETITION
Trep FOR n'th REPETITION
SS(t)
RO(t)
PE(t)
RF PULSE
NMA SIGNAL
INTERVAL
n'th PROGRAMABLE AMPLITUDE PULSE
90°
180°
90°
TE/2
TE
1
2
3
4
1
TIME

FIG. 2

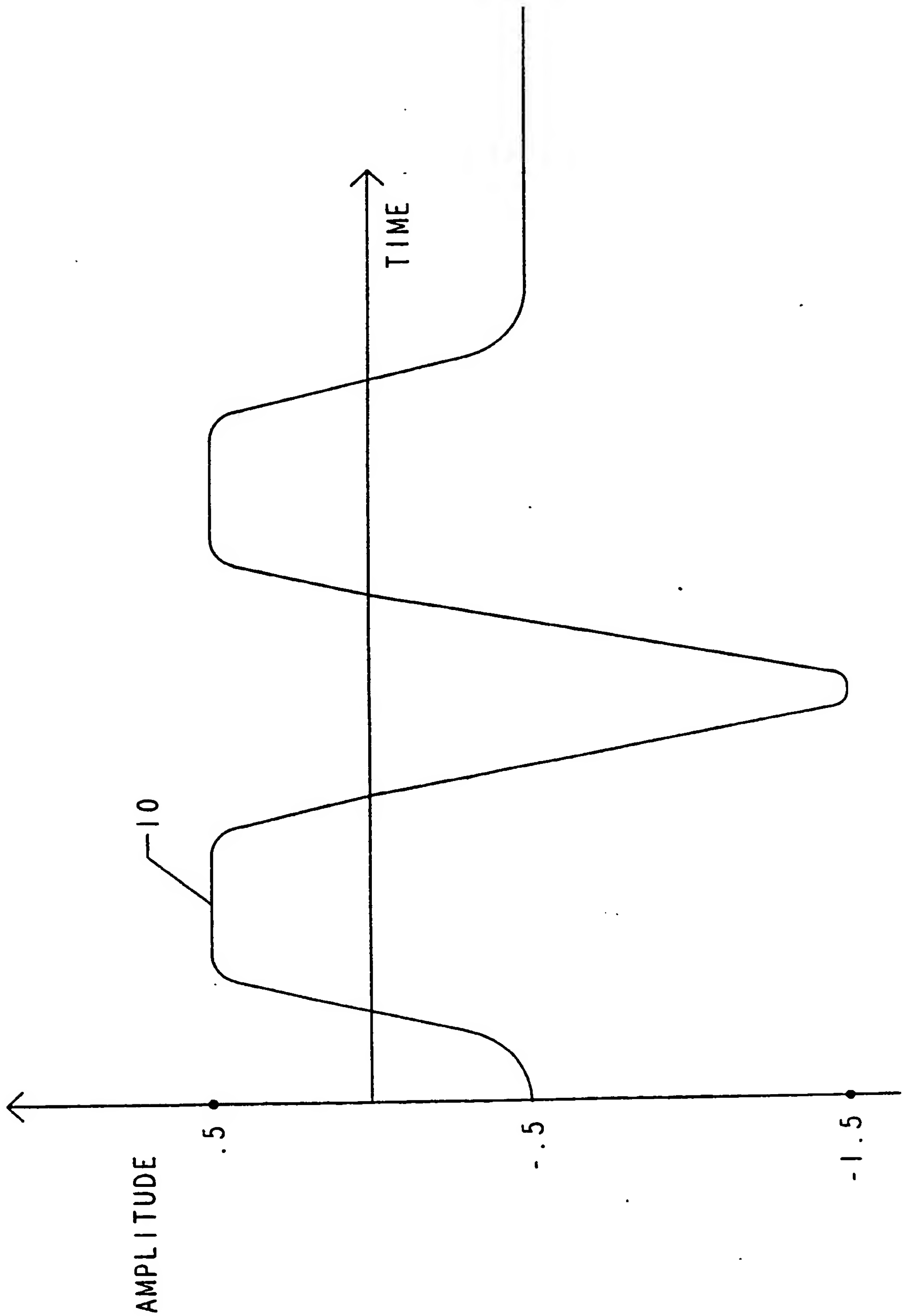


FIG. 3

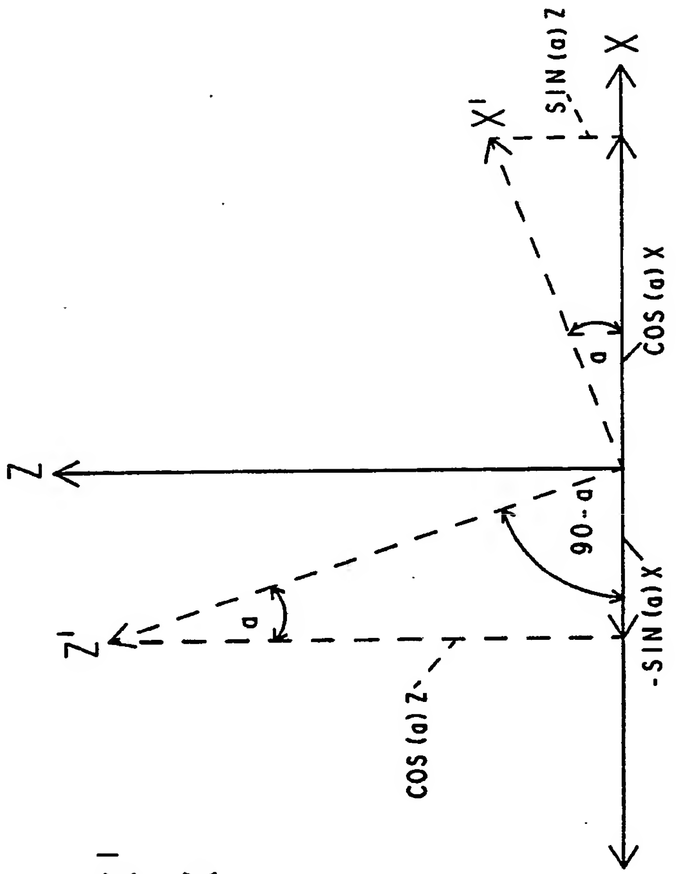


FIG. 5

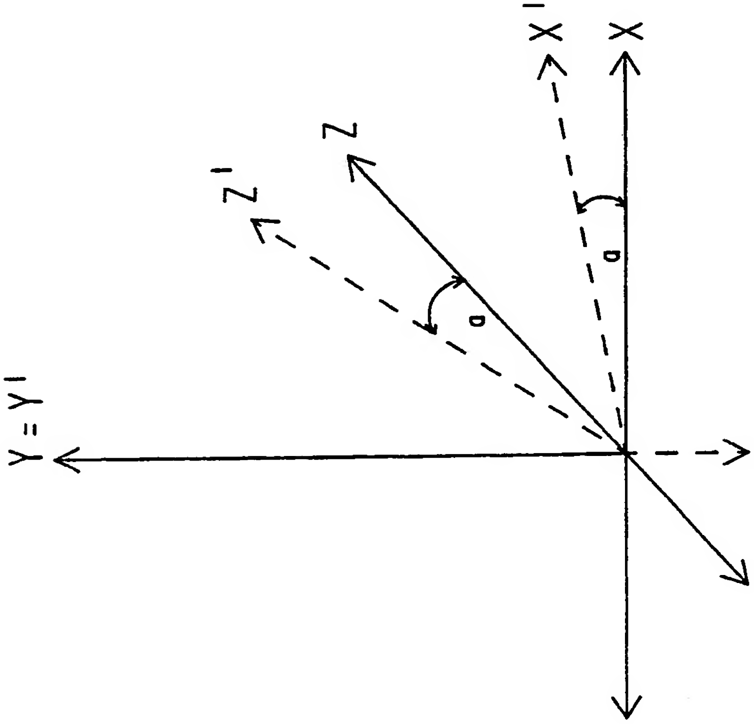


FIG. 4

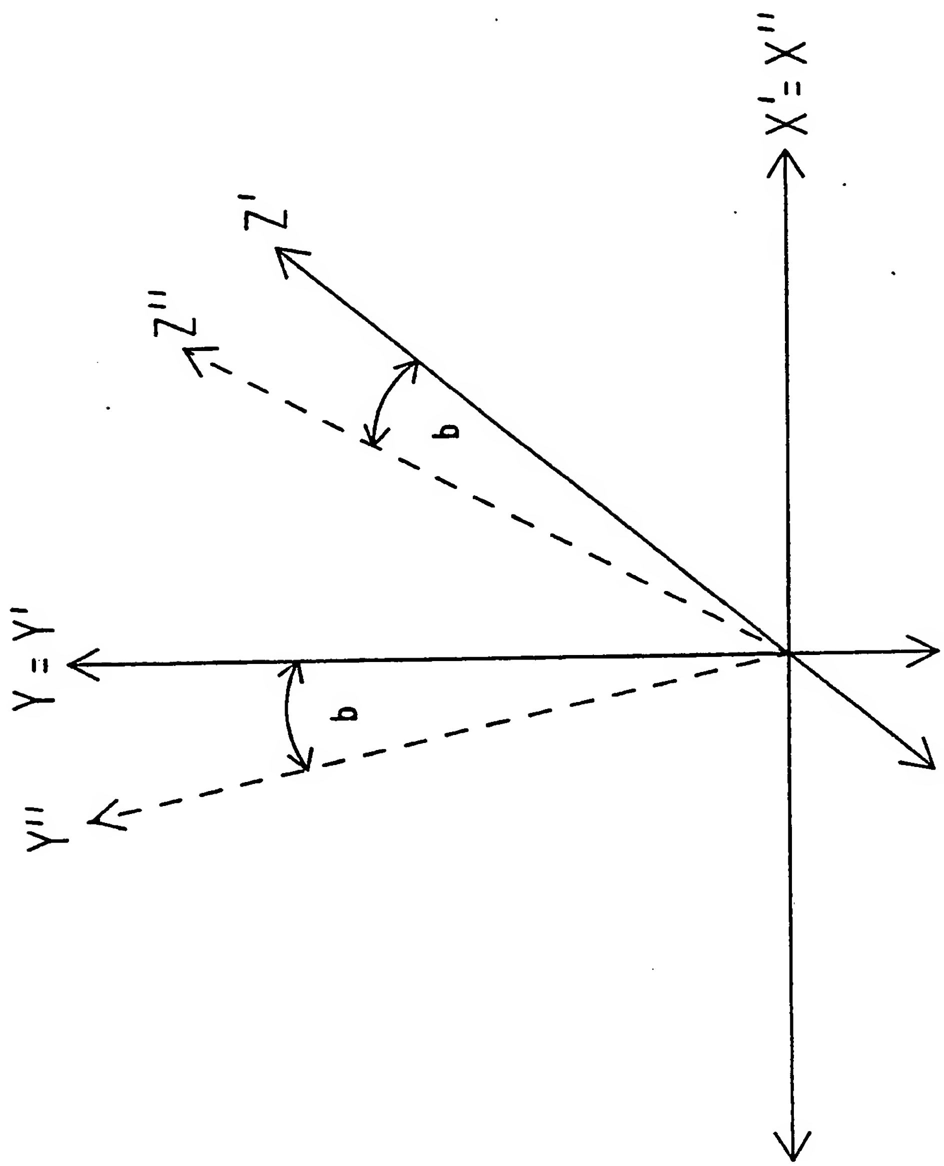


FIG. 6

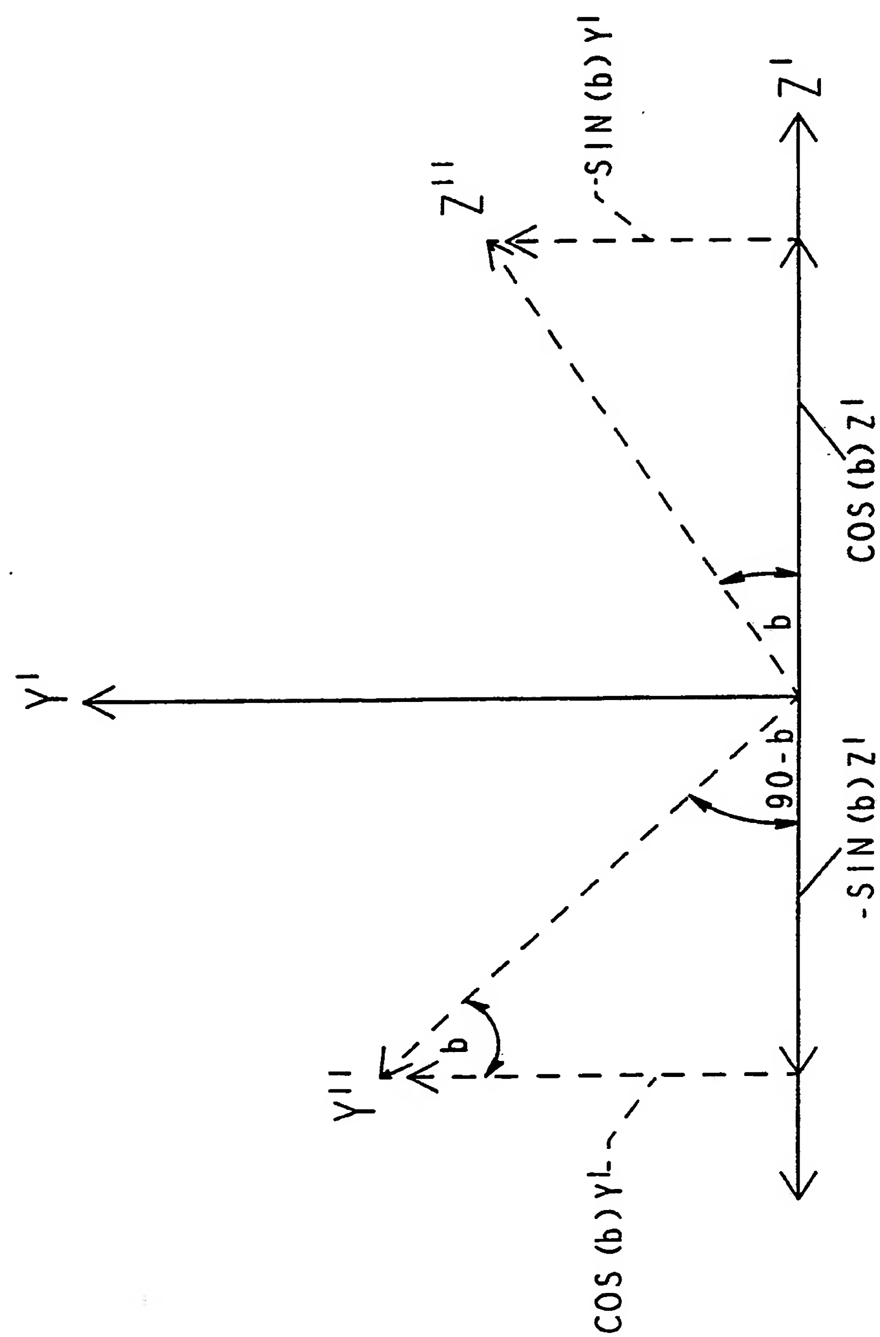


FIG. 7

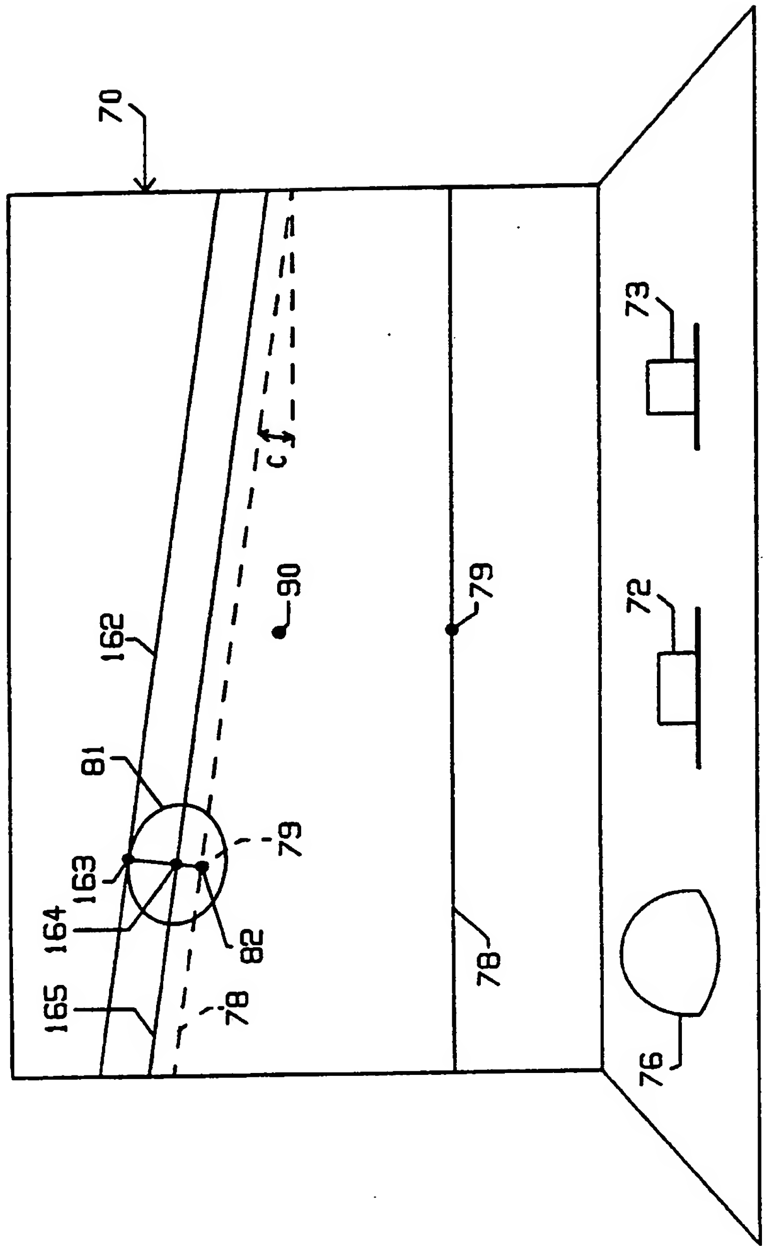


FIG.8

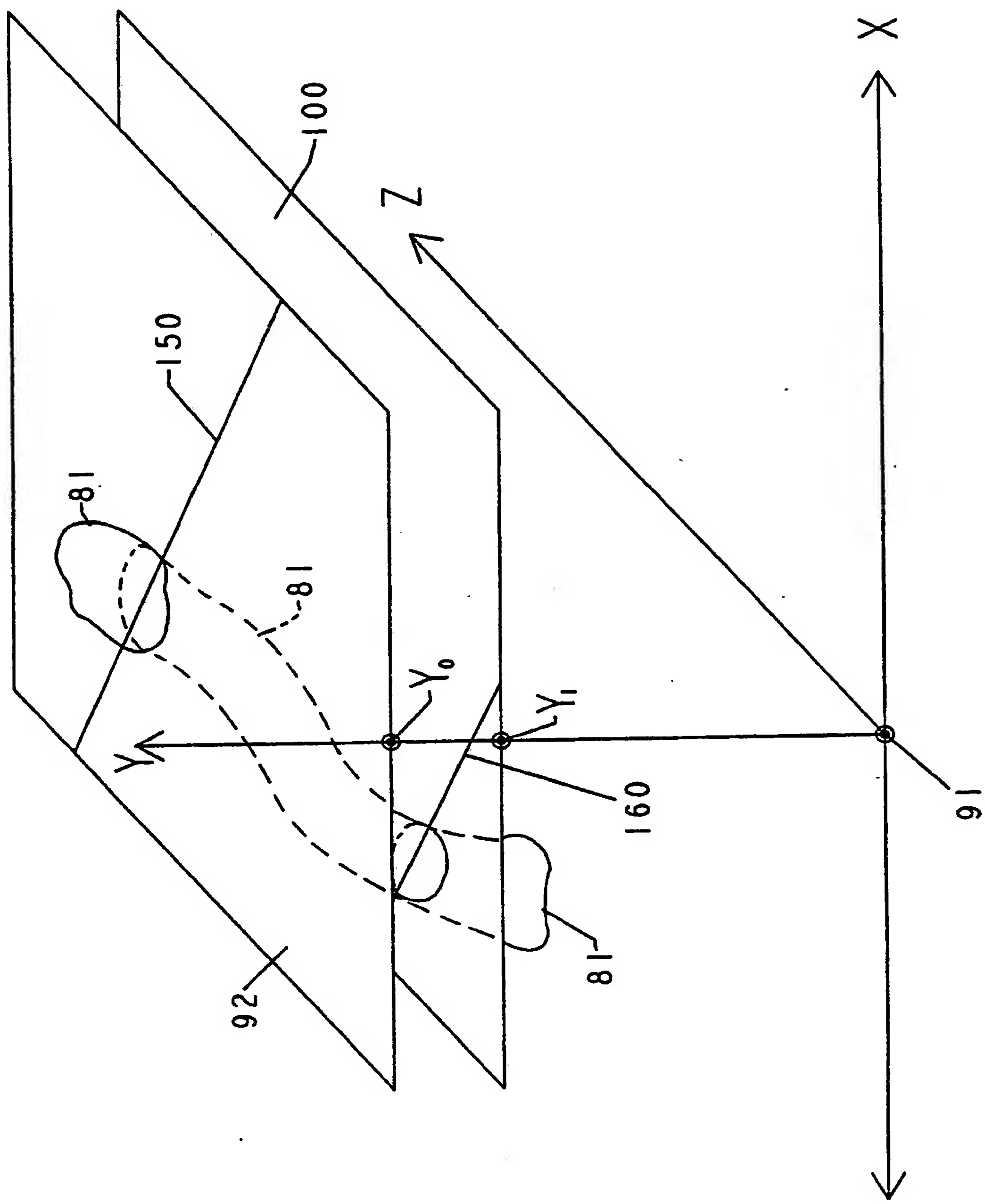


FIG. 9

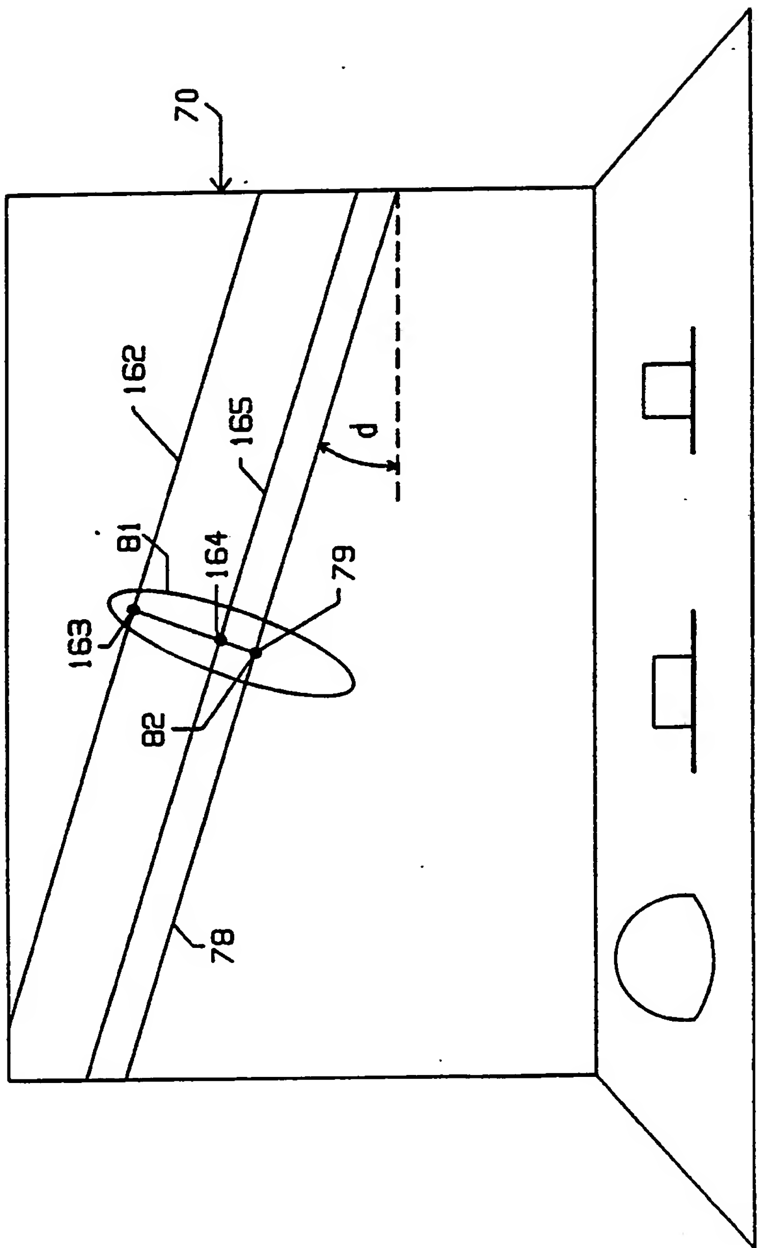
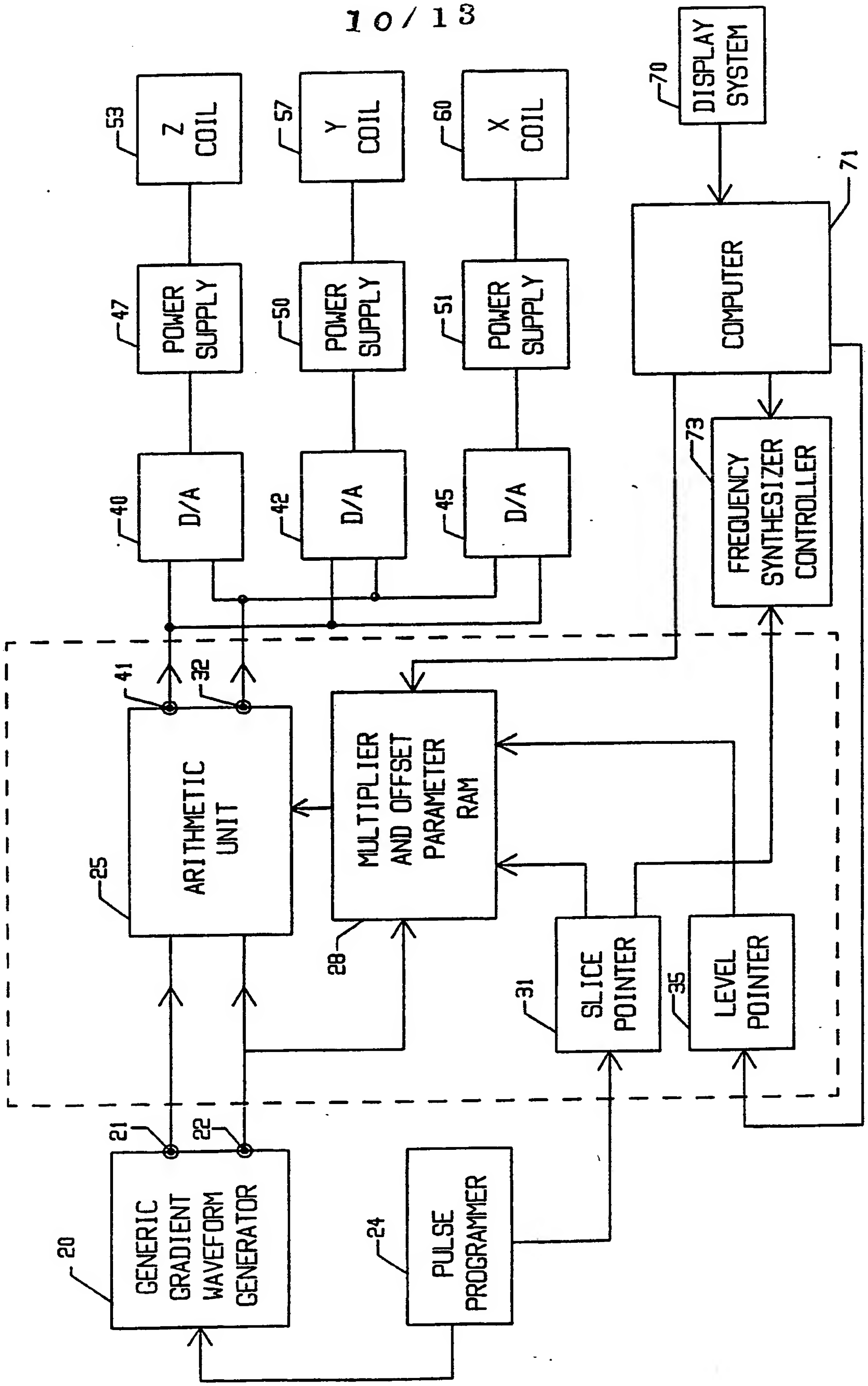


FIG. 10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20
21
22
PULSE PROGRAMMER
24
ARITHMETIC UNIT
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41
32
MULTIPLIER AND OFFSET PARAMETER RAM
28
SLICE POINTER
31
LEVEL POINTER
35
D/A
40
D/A
42
D/A
45
POWER SUPPLY
47
POWER SUPPLY
50
POWER SUPPLY
51
Z COIL
53
Y COIL
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X COIL
60
DISPLAY SYSTEM
70
COMPUTER
71
FREQUENCY SYNTHESIZER CONTROLLER
73

FIG. 11

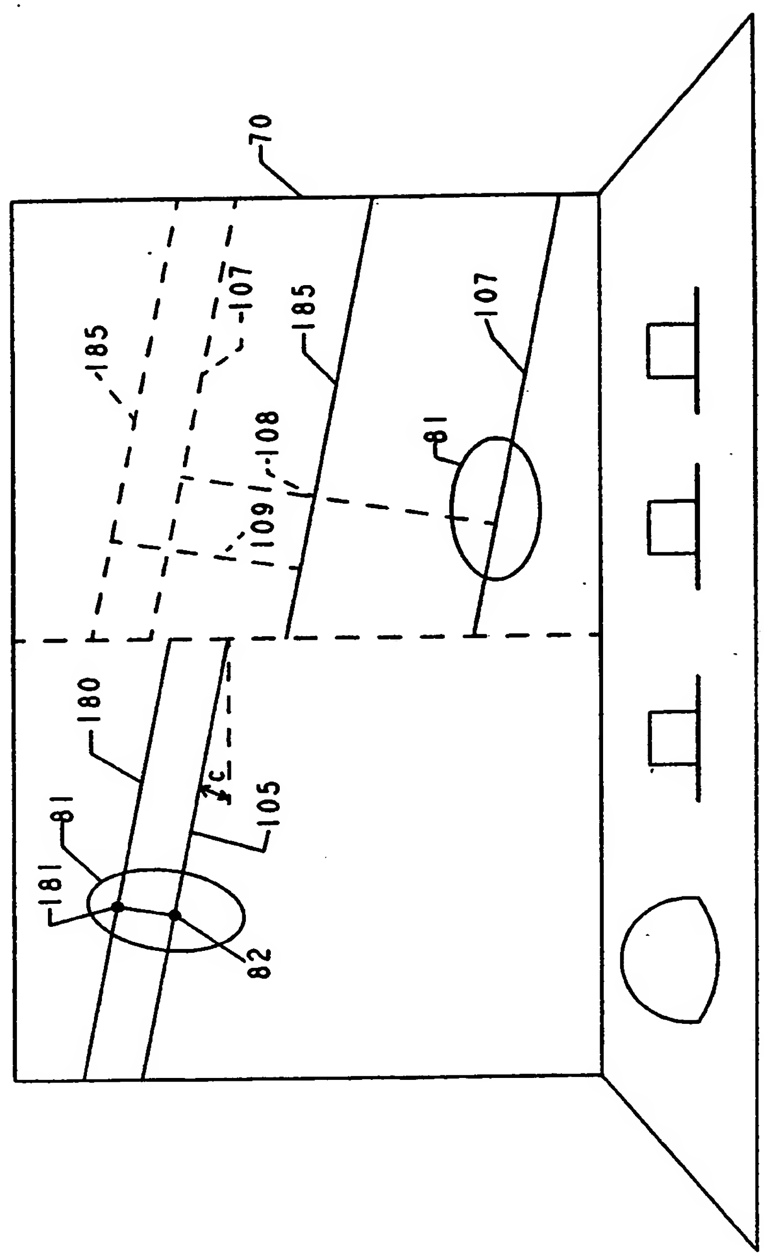
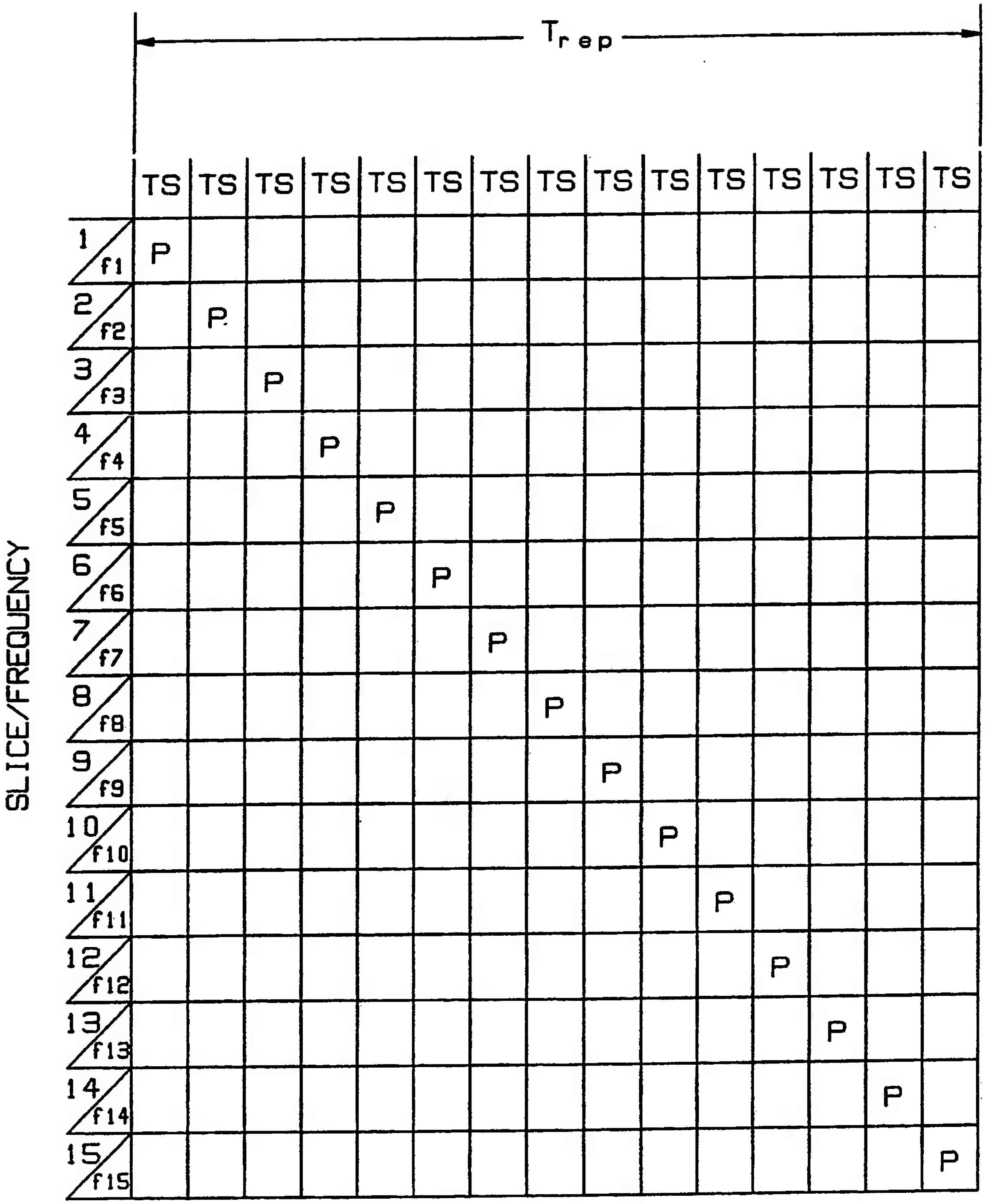


FIG. 12


Trep
TS TS TS TS TS TS TS TS TS TS TS TS TS TS TS
SLICE/FREQUENCY
1 f1
2 f2
3 f3
4 f4
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6 f6
7 f7
8 f8
9 f9
10 f10
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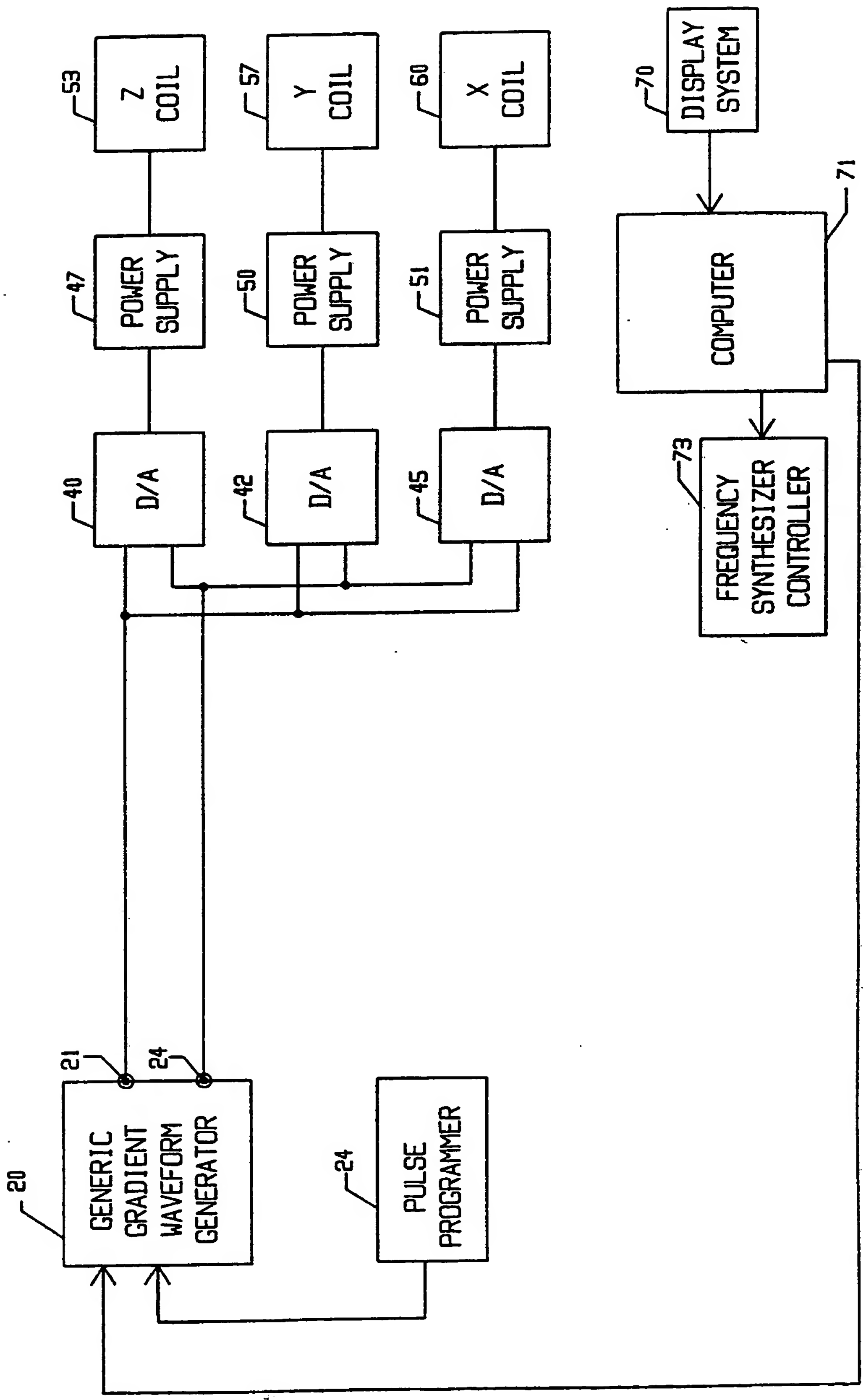
P P P P P P P P P P P P P P P

FIG. 13


53
Z COIL
57
Y COIL
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X COIL
70
DISPLAY SYSTEM
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POWER SUPPLY
50
POWER SUPPLY
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POWER SUPPLY
71
COMPUTER
40
D/A
42
D/A
45
D/A
73
FREQUENCY SYNTHESIZER CONTROLLER
21
24
20
GENERIC GRADIENT WAVEFORM GENERATOR
24
PULSE PROGRAMMER

FIG. 14

INTERNATIONAL SEARCH REPORT

International Application No PCT/US87/03065

I. CLASSIFICATION OF SUBJECT MATTER (if several classification symbols apply, indicate all) [3]

According to International Patent Classification (IPC) or to both National Classification and IPC

IPC 4 GO1R 33/20

U.S. Cl. 324/307, 309

II. FIELDS SEARCHED

Minimum Documentation Searched [4]

Classification System	Classification Symbols
US	324/307, 309

Documentation Searched other than Minimum Documentation to the Extent that such Documents are Included in the Fields Searched [5]

III. DOCUMENTS CONSIDERED TO BE RELEVANT [14]

Category *	Citation of Document, [16] with indication, where appropriate, of the relevant passages [17]	Relevant to Claim No. [18]
X, E	US, A, 4,710,716 (Keren et al.) 01 December 1987, see the entire document.	1-15
A,P	US, A, 4,649,347 (Hwang et al.) 10 March 1987.	
A	US, A, 4,510,448 (Riedl) 09 April 1985.	
A	US, A, 4,322,684 (Hounsfield) 30 March 1982.	

* Special categories of cited documents: [15]

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"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

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"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

IV. CERTIFICATION

Date of the Actual Completion of the International Search [2]	Date of Mailing of this International Search Report [2]
04 February 1988	18 MAR 1988
International Searching Authority [1]	**Signature of Authorized Officer [20]**
ISA/US	Lawrence Fess Lawrence Fess

Form PCT/ISA/210 (second sheet) (May 1986)

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